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TWO-PHASE FLUID FLOW THROUGH NOZZLES AND ABRUPT ENLARGEMENTS

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1. INTRODUCTION

The behavior of a fluid undergoing a phase change from liquid to vapor while flowing through a duct is of interest to engineers in many practical situations. For the case of interest to us, geothermal hot water flowing through various channels (well bores, surface pipes, equipment, etc.) may reach its flash point and choke point under appropriate conditions. The proper design of energy conversion systems depends on the ability of the engineer to predict this behavior with an acceptable degree of accuracy.

The present study was in part motivated by the task of designing the blowdown, two-phase fluid flow test facility at Brown University [1]. In that facility, a refrigerant (dichlorotetrafluorethane or R-114) is boosted to a selected stagnation state and allowed to flow through a nozzle orifice into a long straight tube. The operation relies on the fluid being choked at the inlet section, and under certain circumstances, at the downstream section as well. A simple schematic of the test section is shown in Fig. 1.

This paper treats the problem generically and analytically, making use of the basic laws of fluid mechanics and thermodynamics. Specific calculations have been performed using R-114 as the flowing medium. We attempt to identify and describe all possible flow conditions in and downstream of the nozzle for all possible stagnation conditions.

2. LITERATURE SURVEY

The subject of critical flows of two-phase mixtures has been treated by a large number of investigators both analytically and experimentally, with emphasis on the latter and focused on problems relating to the operation of nuclear power stations.

A recent summary of such work was given by Abuaf et al [2]. Cumo [3] reported on measurements of two-phase jets during transient flow as might occur during a loss-of-coolant-accident (LOCA). Giot [4] discusses methods of predicting the pressure drops associated with two-phase flow through abrupt enlargements, contractions, combinations of enlargements and contractions, sharp-edged orifices, bends, tees and Y's. Watson et al [5] focused on the sharp-edged orifice and developed semi-empirical correlations for pressure drop, quality and mass flow, using water and steam in various combinations of pipe and orifice diameter, but for low quality flows ($x < 0.11$). A freon boiling loop was used by Harshe et al [6] to study pressure drop in a contraction-enlargement section. In their analysis of the results, they allowed for slip between the phases everywhere in the flow except at the vena contracta where the flow was assumed to be homogeneous.

Certain experimenters have investigated flows of two-component, two-phase mixtures, typically air and liquid water; notable among such workers are Dukler and co-workers [7], and Petrick and Swanson [8]. The applicability of results obtained on two-component systems to one-component systems remains an open question owing to the lack of complete thermodynamic similarity between the two cases. It is felt that the latent heat effects play a crucial role in determining the behavior of one-component, two-phase flows. No such effect is present in two-component, two-phase flows.

3. BASIC ASSUMPTIONS AND EQUATIONS

We shall consider the flow of a fluid, either a liquid or a two-phase mixture, through an orifice. The orifice is modeled as a smooth converging nozzle, as shown in Fig. 2. The nozzle is of a certain length, the exit plane of which is labeled as 1 in the figure. The fluid is fed to the nozzle from a large reservoir characterized by certain stagnation properties (state 0) such as P_o, T_o, h_o, s_o, v_o. For this part of the analysis we focus on the control volume, CV-1, between the stagnation state and any arbitrary location, i, inside the nozzle.

The assumptions are:

(1) The flow is horizontal.

(2) Thermal, mechanical, and chemical equilibrium exist between the liquid and vapor phases of the flow.

(3) There is no slip between the phases, i.e., the velocity of the liquid and the vapor phases are the same.

(4) The flow is one-dimensional, i.e., the velocity is perpendicular to the nozzle cross-section and uniform in each cross-section.

(5) The flow is steady, i.e., at each point the fluid properties and velocity do not vary with time. Alternatively we may imagine that small variations have been averaged out over the short time interval associated with an actual measurement, and the sequential measurements are constant within the standard deviation of this averaging process.

(6) The system is adiabatic, i.e., there is no heat transfer between the fluid and its surroundings.

(7) The effect of wall shear stress is negligible.

Thus, the flow process is assumed to take place isentropically between the stagnation state and any point inside the nozzle. We shall deal later with the situation that occurs when the fluid leaves the nozzle and enters the constant-area enlargement.

We now shall apply the usual conservation laws for energy and mass to the fluid contained within control volume CV-1. From conservation of energy (First Law of thermodynamics), we obtain:

$$h_0 = h_1 + 1/2\, w_1^2 \ , \tag{1}$$

and the continuity equation gives

$$\dot{m} = wA/v = \text{constant}. \tag{2}$$

The Second Law may be expressed simply as

$$s_o = s_i. \tag{3}$$

The mass flux, ψ, is defined by rearranging eq. (2) as follows:

$$\psi = \dot{m}/A = w/v = \rho w. \tag{4}$$

Finally the equation of state for the fluid is needed. This may be expressed in general form as

$$f(s, h, v) = 0. \tag{5}$$

It turns out to be convenient to define the following dimensionless parameters:

- Mach number, M,

$$M = w/a. \tag{6}$$

- Reference Mach number, $\bar{M}$;

$$\bar{M} = w/a^* . \tag{7}$$

- Dimensionless mass flux, J;

$$J = \psi/\psi^* . \tag{8}$$

In these equations, the term, a, is the choking velocity, namely,

$$a = \left[\left(\frac{\partial p}{\partial \rho} \right)_s \right]^{1/2} \tag{9}$$

This quantity is well-known for single-phase fluids, and has been calculated for mixtures of liquid and vapor by various people, according to a no-slip (or homogeneous) flow model. Tabulated results are available for water substance, for example, in Ref. [9], and for R114 and water in Ref. [10]. The term, a^*, is the choking velocity at the flash point, i.e., under saturation conditions reached isentropically from the stagnation state. The term, ψ^*, is given by

$$\psi^* = a^*/v^* , \tag{10}$$

and is a reference mass flux achieved when the fluid flashes and chokes simultaneously with a velocity just equal to the choking velocity, i.e., when $w = w^* = a^*$, or $M = \bar{M} = 1$.

4. NOZZLE FLOW AS A FUNCTION OF "BOOST"

The flow through the nozzle will be described as a function of the "boost"--the excess enthalpy, i.e., stagnation enthalpy minus the saturation enthalpy for an isentropic process starting from the stagnation state:

$$\text{boost} \equiv h_o(P_o, s_o) - h^*(s_o) \tag{11a}$$

$$= v^*(s_o) \times \{ P_o - P^*(s_o) \} . \tag{11b}$$

In the description that follows, we will assume that the fluid is choked at the nozzle exit. We discern five cases of interest.

- Case 1: $h_o = h_o^*$. See Fig. 3(a).

The stagnation enthalpy is equal to that value which causes the fluid to reach the choking velocity just as it reaches the flash point. For this special case, the reference Mach number equals unity; i.e.,

$$\bar{M} = \frac{w}{a^*} = \frac{w^*}{a^*} = \frac{a^*}{a^*} = 1. \tag{12}$$

Furthermore, the dimensionless mass flux is also equal to unity; i.e.,

$$J = \frac{\psi}{\psi^*} = \frac{\psi^*}{\psi^*} = 1. \tag{13}$$

The fluid flows as a compressed liquid through the nozzle and reaches its flash point and chokes simultaneously at the end of the nozzle.

- Case 2: $h_o > h_o^*$. See Fig. 3(b).

Since the boost in this case is greater than in Case 1, the fluid flows as a compressed liquid up to the flash point where it immediately chokes because its velocity will exceed the local choking velocity. Thus, $\bar{M} > 1$.

- Case 3: $h_o^* > h_o > h^*$. See Fig. 3(c).

Here the stagnation enthalpy lies between the value of h_o^* and the saturation enthalpy for the isentropic process. For this case there is insufficient boost to cause the fluid to choke upon flashing. Thus the fluid first flashes at some point inside the nozzle with a subcritical velocity, and then continues to accelerate until it reaches the choking velocity as a two-phase mixture. The choking point must, of course, be at the end of the nozzle since the Mach number reaches unity at that point and the mass flux is a maximum.

- Case 4: $h_o = h^*$. See Fig. 3(d).

For this case the reservoir conditions are those of a saturated liquid so the fluid flashes immediately upon entering the nozzle. Since the fluid is assumed to start from a stagnation state, i.e., $w_o = 0$, then the reference Mach number starts from zero, i.e., $\bar{M} = 0$. The fluid will choke as a two-phase mixture, as soon as it reaches the local choking velocity, a.

- Case 5: $h_o < h^*$. See Fig. 3(e).

This case is similar to Case 4 except that the initial conditions consist of a two-phase mixture at the stagnation state.

These five cases can be visualized with the aid of the (ψ, w)-diagram given in Fig. 4. Here we have plotted the mass flux versus the fluid velocity. The steep straight line represents purely liquid flow where the density is essentially constant, i.e.,

$$\psi = \rho_f w = \text{constant} \times w . \tag{14}$$

One can imagine a sequence of fluid state points starting from the origin and proceeding up the liquid line until the flash point is reached. As long as the fluid is not choked, it can continue from the flash point as a two-phase mixture along one of the branch curves until the choking point is reached, i.e., until one reaches the maximum in ψ. This will signify the end of the nozzle for the chosen conditions. Each branch curve in Fig. 4 represents a constant value of boost or a particular stagnation enthalpy. The entropy is constant and equal to s_o for all processes.

The upper two branch curves, (1) and (2), are for Case 2 where the fluid flashes with $\bar{M} > 1$. Thus the curves are hypothetical since the fluid remains a liquid throughout the nozzle, and we would need to insert a smooth diverging section following the throat for the fluid to continue along a branch with increasing velocity. That is, we would need a DeLaval nozzle to carry the fluid into the two-phase supersonic regime. A similar conclusion can be drawn for the next lower branch curve, (3), Case 1, where it can be seen that the fluid flashes and chokes with $M = 1$, $\bar{M} = 1$, and $\psi = \psi^*$. At this point the branch curve has a horizontal tangent.

The remaining five branch curves, (4)-(8), all exhibit a maximum, i.e., a point where the mass flux reaches its greatest value, namely, its choking mass flux. The loci of these maxima trace the line, $M = 1$. Physically realizable flow states must proceed from the liquid line and up the rising portion of these branches to the point where $M = 1$; flows continuing down the descending portions would violate the equations of motion if the nozzle extended beyond the point where $M = 1$ with a decreasing cross-sectional area. Again a DeLaval nozzle would be required. Although it may not be obvious from the schematic diagram, Fig. 4, the branch curve for $h_o = h^*$ is tangent to the line $\psi = \rho_f w$ at the origin, $\psi = w = 0$.

It is clear from Fig. 3 that the flow need not be choked in all cases. As long as the pressure at the end of the nozzle, P_e, is greater than the choking pressure, P_c, then the flow will not be choked. For Cases 1 and 2, the unchoked flow will reach the exit as a compressed liquid; for Cases 4 and 5, it will emerge as a two-phase mixture; for Case 3, if $P_e > P_{sat}$, it will leave as a compressed liquid, and if $P_{sat} > P_e > P_c$, it will leave in a two-phase state.

5. NOZZLE PERFORMANCE CURVES

Nozzle performance curves can be drawn up from the solution of eqs. (1-5) together with the appropriate choking velocity and the definitions given in eqs. (6-8). The method is straightforward. The stagnation properties are specified for a given working fluid. Successive values of enthalpy, h_i, are selected; velocity values, w_i, are then found from eq. (1). The specific volume, v, can be found using eqs. (3) and (5), and the mass flux, ψ, is then calculated from eq. (4). The choking velocity, a, is found for the selected fluid conditions from eq. (9) or

Refs. [9] or [10], and the velocity, w, is compared with it to see whether the chosen state is subcritical, critical, or supercritical.

Detailed calculations have been carried out for refrigerant-114 (R114), and the results are shown in Fig. 5. The coordinates are similar to those used in the illustrative diagram, Fig. 4, except that they have been made dimensionless: the ordinate is the dimensionless mass flux, J, and the abscissa is the reference Mach number, $\overline{M}$.

The diagram shows performance curves for the following values of the parameters:

$$\frac{a^*}{v^*} = 3734.4 \quad kg/(s \cdot m^2),$$

$$a^* = 2.56 \quad m/s,$$

$$h^* = 24.654 \quad kJ/kg,$$

and

$$T^* = T_o = 25°C.$$

One will notice that the constant boost lines are actually plotted as lines of $h_o - h^*$ = constant in accordance with the definition given in eq. (11a). Also shown are several lines of constant Mach number, constant quality, constant values of v/v_f, and constant ΔT where ΔT is the difference between the flash temperature and the local fluid temperature. A pair of auxiliary curves at T^* = 20°C and 30°C are also included to show the effect of changes in stagnation temperature. These are shown as broken and dashed lines, respectively.

6. NOZZLE FLOW FOR VARYING BACK-PRESSURE

For this part of our study we shall take the reservoir or stagnation conditions as fixed, and examine the effect of changes in the downstream pressure, P_2, as shown in Fig. 2. In a practical sense, this represents the case of controlling the flow from the reservoir, through the orifice, and into the pipe, as illustrated in Fig. 1, by setting the opening of the downstream control valve, i.e., by setting the pressure, P_g.

Before we tackle the problem quantitatively, let us first describe qualitatively the nature of the flow as a function of the pressure, P_g. It should be understood that P_2 is measured just downstream of the point where the issuing jet attaches itself to the wall of the pipe, and corresponds to the place where we can once again treat the flow as one-dimensional. Since a free, turbulent jet spreads with a roughly constant half-angle of 13° [11], this point may be closely approximated in practice.

The pressure drop along the pipe from station 2 to the control valve where P_g is measured will depend on the nature of the flow between these points, e.g., liquid only, two-phase, etc. We shall not consider this latter aspect of the flow, but shall concentrate on the flow from state 0 to state 2.

The nature of the flow depends on the amount of boost. Let us assume that $h_o \geq h_o^*$, i.e., Cases (1) and (2). See Figs. 3(a) and 3(b). Initially suppose that the pressure is uniform throughout the system with $P_2 = P_o$. There will be no flow. This is Case I shown in Fig. 6(a). When P_2 is lowered to a value slightly less than P_o, (Case II), flow will begin. The pressure falls through the nozzle, and the fluid leaves the nozzle with an exit velocity less than the choking velocity, separates from the nozzle, expands as a free jet, and attaches itself to the wall of the straight pipe. Pressure recovery is incomplete during the expansion because of entropy production associated with the jet process. The pressure in the separated region, P_s, is equal to that at the exit plane, P_1.

As P_2 is lowered further, the mass flow rate increases and the nozzle exit pressure falls (Case III). At a particular value, (Case IV), the nozzle exit pressure reaches the saturation pressure for the given stagnation conditions and the fluid flashes and chokes at the nozzle exit. We shall call this particular back pressure P_2^c. As the jet immediately begins to expand, the pressure increases and the fluid returns to a compressed liquid condition. The details of that process are beyond the scope of this analysis.

For values of $P_2 < P_2^c$, (Case V), a complex fluid process, consisting of Prandtl-Meyer expansions, oblique and normal shock waves, occurs in the highly turbulent jet. The process may even be reasonably isentropic for a short distance downstream of the exit plane of the nozzle. In any event, we are interested in the state of the fluid at position 2.

In a similar fashion one may describe what takes place when the boost is such that $h^* < h_o < h_o^*$, i.e., Case (3). See Fig. 3(c). It ought to be mentioned, however, that in practice h_o^* is so close to h^* that such a condition is very difficult to create. This is a result of the extremely low choking velocities encountered along the saturated liquid line. Thus only a tiny boost is necessary to accelerate the fluid to its choking velocity when it flashes.

Nevertheless, for such a condition, Cases I, II, and III, as shown in Fig. 6(a) would apply here as well. See I, II, and III in Fig. 6(b). At a certain back pressure, P_2^s, the pressure at the nozzle exit reaches the saturation pressure, $P_1 = P_{sat}$, and the fluid flashes, but does not choke (Case IV'). For P_2 slightly less than P_2^s, the fluid flashes inside the nozzle, flows to the exit as a two-phase mixture, expands as a two-phase jet, and may recover sufficient pressure to recondense before it attaches itself to the wall (Case V'). Eventually P_2 may be reduced to a value P_2^c that causes the two-phase mixture to choke at the exit (Case VI'). Further reduction in P_2 will result in the kind of complex flow processes described above for Case V, shown as Cases VII' and VIII' in Fig. 6(b). As the back-pressure P_2 is reduced below P_2^s, the flash front moves upstream from the nozzle exit plane until the fluid chokes, at which point the flash front remains fixed.

The similarity between Figs. 6(a) and 6(b) and the well-known analogous figure for one-dimensional compressible flow through a converging-diverging nozzle is apparent.

7. ANALYSIS OF FLOW DOWNSTREAM OF NOZZLE EXIT

We focus now on the control volume CV-2 in Fig. 2, i.e., from the exit plane of the nozzle to a point just downstream of the point where the jet attaches itself to the pipe wall, and including the region of separated flow.

The continuity equation gives

$$\dot{m} = w_1 A_1/v_1 = w_2 A_2/v_2 \ , \tag{15a}$$

or

$$\dot{m} = \psi_1 A_1 = \psi_2 A_2 \ , \tag{15b}$$

where A_1 is the exit area of the nozzle.

The energy equation may be written as

$$h_o = h_1 + 1/2\ w_1^{\ 2} = h_2 + 1/2\ w_2^{\ 2} \ . \tag{16}$$

In writing the momentum equation we must be careful to distinguish between the cases where the flow is choked or not choked at the nozzle exit. As long as the flow is not choked the pressure in the separated region, P_s , will be equal to the pressure in the exit plane of the nozzle, P_1. Under choked condition, the pressure in the exit plane will not, in general, be equal to the pressure in the separated region. They will be equal only for the special case when the back pressure, P_2 , is the maximum value to produce choked conditions at state 1. For any lower back pressure, the pressure P_1 remains fixed at its choked value whereas P_s decreases according to the back pressure.

In general the momentum equation may be expressed in the form

$$\dot{m}(w_2 - w_1) = P_1 A_1 + P_s(A_2 - A_1) - P_2 A_2 \ . \tag{17}$$

As long as the flow is not choked, P_1 and P_s are identical, and eq.(17) becomes

$$\dot{m}(w_2 - w_1) = A_2\,(P_1 - P_2)\ . \tag{18}$$

When P_2 is the maximum value possible under choked flow conditions, i.e., when $P_2 = P_2^{\,c}$, eq. (17) may be written as

$$\dot{m}_c(w_2 - a_1) = A_2(P_1 - P_2^{\,c})\ . \tag{19}$$

For choked flow with any lower value of P_2, $P_2 < P_2^{\,c}$, the momentum equation is

$$m_c(w_2 - a_1) = P_{1c}\,A_1 + P_s(A_2 - A_1) - P_2\,A_2\ . \tag{20}$$

The equation of state for a one-component pure substance, as before, is given by

$$f(s,\ h,\ v) = 0. \tag{5}$$

As long as the flow is not choked, we can combine eqs. (15a) and (18) to give the following expression for P_1 in terms of P_2:

$$P_1 = P_2 + \frac{w_1^{\,2}}{v_1} \times \left(r\ \frac{v_2}{v_1} - 1\right)r\ , \tag{21}$$

where $r \equiv A_1/A_2$. Unfortunately this equation by itself does not in general allow us to calculate P_1 from a known P_2 because the specific volume v_2 is a function of both P_2 and s_2, the latter of which remains unknown. Owing to the dissipative separation process, the Second Law requires

$$s_2 \geq s_0\ . \tag{22}$$

However, a drastic simplification becomes possible for the special case where the fluid is in the liquid state at both section 1 and 2. We may write the Bernoulli equation for CV-1 between states 0 and 1:

$$P_0 = P_1 + \frac{w_1^{\,2}}{2v_1}\ . \tag{23}$$

Solving this for $w_1^{\,2}$, substituting into eq. (21), and rearranging, we find

$$P_2 = \left(2r^2\ \frac{v_2}{v_1} - 2r + 1\right)P_1 - \left(2r^2\ \frac{v_2}{v_1} - 2r\right)P_0\ . \tag{24}$$

But since there is liquid at states 0, 1, and 2,

$$v_2 \approx v_1 \approx v_o \approx \text{constant}, \tag{25}$$

and

$$P_2 = (2r^2 - 2r + 1)P_1 - 2r(r-1)P_o . \tag{26}$$

Thus for this special case, P_1 and P_2 are linearly related, i.e., as long as the flow is <u>not choked</u> and is in the <u>liquid state at 0, 1, and 2</u>.

Turning now to the case of <u>choked flow</u>, we may combine eqs. (15), (16), and (18) to obtain the following equation for the pressure in the separated region:

$$P_s = \frac{1}{1-r} \left\{ P_2 - r(P_{1c} + \frac{a_1^2}{v_{1c}}) + v_2 \psi_2^2 \right\} . \tag{27}$$

Once again we are unable to calculate either P_s or P_2 from the other, exactly, since v_2 depends on both P_2 and the unknown s_2. But as before we are able to use the approximation, $v_2 \approx v_o$, as long as the fluid is in the <u>liquid</u> state at 0 and 2. Thus, we may use eq. (27) to find P_s for any value of P_2 under these conditions since all the other terms - r, P_{1c} , a_1, v_{1c}, ψ_2 , and $v_2 \approx v_o$ - are known constants. Again, the equation becomes linear in P_s and P_2 for these conditions.

We may shed some light on the effect on P_s of variations in P_2 under choked conditions by implicit differentiation of eq. (27):

$$dP_s = \frac{1}{1-r} \left\{ dP_2 + \psi_2^2 \, dv_2 \right\} . \tag{28}$$

Similarly from eqs. (4) and (15) we find

$$dw_2 = \psi_2 \, dv_2 , \tag{29}$$

and from eq. (17), we find

$$dh_2 = -w_2 \, dw_2 . \tag{30}$$

From eqs. (29) and (30) together with $\psi_2 = w_2/v_2$, it follows that

$$dh_2 = -\psi_2^2 \, v_2 \, dv_2 \; . \tag{31}$$

The Gibbs equation applied to section 2 is

$$T_2 \, ds_2 = dh_2 - v_2 \, dP_2 \; . \tag{32}$$

The last two equations combine to form

$$dP_2 + \psi_2^2 \, dv_2 = -(T_2/v_2) \, ds_2 \; . \tag{33}$$

The left-hand side of eq.(33) is just the bracketed term in eq.(28); thus,

$$dP_s = - \left[\frac{1}{1-r} \; \frac{T_2}{v_2} \right] ds_2 \; . \tag{34}$$

Since the bracketed term in eq.(34) is always positive ($0 < r < 1$ by definition), we see that P_s and s_2 are inversely related, i.e., the pressure in the separated region can only decrease whenever the entropy at state 2 increases.

If we now view the problem from the perspective of the classic Fanno-type flow problem and consider the overall control volume consisting of the union of CV-1 and CV-2, the energy equation, eq.(10), may be combined with the continuity equation, eq.(8), to yield

$$h_o = h_2 + \frac{1}{2} \left(\frac{\dot{m}}{A_2} \right)^2 v_2^2 \; , \tag{35}$$

where $\dot{m}$ can be any value not greater than the choking mass flow rate, $\dot{m}_c$. The equation of state, eq.(5), may be expressed as

$$s_2 = f(h_2, \, v_2) . \tag{36}$$

Thus it is a simple matter to compute all possible states 2, i.e., all possible combinations of enthalpy and entropy, for a given pipe size, given stagnation conditions and a specified mass flow rate. A value is selected for v_2 and eq.(35) is solved for h_2. From these values, one finds s_2 from eq.(36) which is usually represented as a set of correlations programmed on a computer.

In particular we may find the solution curve for the case when the flow is choked, i.e., when $\dot{m} = \dot{m}_c$ is at its maximum value. Under those conditions we may also determine the appropriate back pressure from the equation of state expressed in the form

$$P_2 = f(h_2, s_2). \tag{37}$$

With this in hand, we can return to eq.(27) and calculate the corresponding pressure in the separated region, P_s .

Thus we are able to construct a Mollier diagram (h,s coordinates) to show the various processes as well as a diagram of P_s versus P_2. These are given schematically in Figs. 7 and 9, respectively.

Figure 7 shows the behavior of the system for choked conditions at the nozzle exit and for $h_o \geq h_o^*$. Thus the flow chokes and flashes at the exit of the nozzle. Various back pressures, P_2, will produce corresponding states 2 along the Fanno line as can be seen, starting from $P_2 = P_{2c}$ and for lower values. It will be observed that the final state 2 may be: (a) compressed liquid if $P_2^c < P_2 < P_2^s$; (b) saturated liquid if $P_2 = P_2^s$; or (c) two-phase, liquid and vapor if $P_2 < P_2^s$. The superscript "s" refers to the condition of saturation.

The pressure P_2^s where the Fanno line crosses the saturated liquid line is easily calculated. The enthalpy may be computed from eq.(35) using known values of h_o, $\dot{m}$, A_2, and $v_2 = v_f$ where v_f is taken as the specific volume of the saturated liquid at the temperature T_o; i.e.,

$$h_2^s = h_o - \frac{1}{2}\left(\frac{\dot{m}}{A_2}\right)^2 v_f^2 . \tag{38}$$

Using the equations of state, eqs.(36) and (37), or in practice, tables or correlations of properties, we can then find the entropy, s_2^s, and the pressure, P_2^s:

$$s_2^s = f(h_2^s, v_f), \tag{36a}$$

and

$$P_2^s = f(h_2^s, s_2^s). \tag{37a}$$

The lowest back pressure possible at state 2, consistent with the Second Law of thermodynamics, is $P_2 = P_{2c}$, which represents the case when the flow experiences a second choke, at the position 2.

Although it cannot be treated explicitly under our assumptions, for $P_2 < P_{2c}$ it may happen in reality that expansion occurs in the jet from state 1 to some state within the two-phase region before the "jump" to the Fanno line. Should this occur it is possible that the jump would involve the recondensation of a two-phase jet to a compressed liquid for a particular range of back pressures. Figure 8 illustrates this schematically. We show this effect occurring over a range of $P_2' < P_2 < P_2^s$. Neither P_2' nor the location of the recondensation point R can be calculated from our analysis. It is interesting to note that this effect has been observed experimentally in the Brown University Two-Phase Test Facility. As a further note, it should be appreciated that this type of "jump" is theoretically possible within our model for stagnation conditions $h^* < h_o < h_o^*$ (Case(3), Fig. 3(a)), but the extension from state 1 into the two-phase region follows an isentrope.

Figure 9 gives the relationship between the pressure in the separated region, P_s, and the back pressure P_2. Starting from no-flow conditions at point 0, P_s falls linearly with P_2 according to eq.(26) until the flow is choked at the nozzle exit. As P_2 falls below P_2^c the relation becomes non-linear and results from the solution of eq.(27) and the Fanno line. At the point 2 where this curve passes through a minimum, the back pressure just reaches a value, P_{2c}, where the flow is also choked at section 2. The pressure in the separated region is then P_s^c and cannot decrease further as long as the flow is choked at section 2. For such a case, section 2 must occur at the end of the straight pipe. Of course P_{2c} cannot be decreased even if the pressure further downstream (for example, in a large receiver vessel) is somehow reduced. Since we are not interested in such cases for this study, the curve relating P_s to P_2 will simply end at point 2 in Fig. 9.

It should be noted that P_s may exceed P_2 before the flow is choked at section 2. This occurs at point E in Fig. 9 for which we may substitute $P_2 = P_s = P_{2E}$ in eq. (27) to obtain

$$P_{2E} = P_{1c} + \frac{a_1^2}{v_{1c}} - \frac{v_2 \psi_2^2}{r} . \tag{39}$$

The solution of this equation along with the Fanno line will yield P_{2E}.

8. SUMMARY: RANGE OF DOWNSTREAM CONDITIONS FOR GIVEN UPSTREAM CONDITIONS

In order to describe the possible conditions that may be achieved downstream of the expanding jet (i.e., at station 2), it is essential to keep the following questions in mind:

- Is the flow at the nozzle exit choked or not?
- What is the stagnation enthalpy (or boost) relative to the quantities h_o^* and h^*?
- What is the relative magnitude of the pressures P_2^c and P_2^s?
- What is the actual downstream pressure P_2 relative to P_2^c and P_2^s?

Depending on the answers to these questions, the state of the fluid at location 2 may be a compressed liquid, saturated liquid, or a two-phase mixture.

We shall attempt to cover all possible cases in an encyclopedic fashion. In all cases bear in mind that the details of the "jump" from state 1 to 2 are beyond the scope of the present study.

CASE I. CHOKED FLOW AT NOZZLE EXIT: $P_2 \leq P_2^c$.

A. If $h^o < h_o^*$, then state 1 is always saturated liquid, and
   1. If $P_2^c > P_2^s$, then state 2 will be:
      a. compressed liquid if $P_2^c > P_2 > P_2^s$,
      b. saturated liquid if $P_2 = P_2^s$, or
      c. two-phase mixture if $P_2 < P_2^s$.

2. If $P_2^c \leq P_2^s$, then state 2 cannot be a compressed liquid, and state 2 will be:

   a. saturated liquid if $P_2 = P_2^s$, or

   b. two-phase mixture if $P_2 < P_2^s$.

Cases I. A. 1 and 2 are depicted in Fig. 10(a).

B. If $h^* \leq h^o < h_o^*$, then state 1 is always a two-phase mixture, and state 2 can only be a compressed liquid providedthe following three conditions are met:

   1. $P_2^c > P_2^s$,

   2. $P_2^s < P_2 < P_2^c$, and

   3. $h_2^s > h^*$.

Case I. B is depicted in Fig. 10(b).

C. If $h^o < h^*$, state 2 can never be a compressed or saturated liquid, and only two-phase mixtures are possible at state 2, as can be seen from Fig. 10(c).

<u>CASE II.</u> <u>FLOW NOT CHOKED AT NOZZLE EXIT:</u> $P_2 > P_2^c$.

A. If $h^o > h_o^*$, then state 1 is always compressed liquid, and:

   1. If $P_2^c > P_2^s$, then state 2 must be compressed liquid;

   2. If $P_2^c = P_2^s$, then state 2 will be:

      a. compressed liquid if $P_2 > P_2^s$, or

      b. saturated liquid if $P_2 = P_2^s$;

   3. If $P_2^c < P_2^s$, then state 2 will be:

      a. compressed liquid if $P_2 > P_2^s$,

      b. saturated liquid if $P_2 = P_2^s$, or

      c. two-phase mixture if $P_2^c < P_2 < P_2^s$.

Case II. A is depicted in Fig. 11(a).

B. If $h^* < h^o < h_o^*$, then:

1. If state 1 is compressed or saturated liquid, the situation is the same as for Case II. A.
2. If state 1 is a two-phase mixture, then:
   a. If $P_2^c > P_2^s$, then state 2 must be compressed liquid;
   b. If $P_2^c = P_2^s$, then state 2 will be as described under Case II. A. 2;
   c. If $P_2^c < P_2^s$, then state 2 will be as described under Case II. A. 3.

Case II. B. 2 is depicted in Fig. 11(b).

C. If $h^o < h^*$, state 2 can only be a two-phase mixture, as shown in Fig. 11(c).

Once again we wish to emphasize that the dashed lines connecting states 1 to states 2 are merely schematic and do not represent a well-defined process. However, the method described in this study does allow the overall entropy change, $\Delta s = s_2 - s_1$, to be calculated using the fact that $s_1 = s_o$ and eq. (36).

9. SAMPLE RESULTS FOR REFRIGERANT 114

A program has been written in BASIC for use on a Hewlett-Packard Model HP-85 desktop computer to give the flash and choke conditions in R-114. The listing of the program is given in the Appendix [12].

For given reservoir conditions, and sizes of the orifice and downstream pipe, the program provides the following information:

- Flash-point and choking conditions at the exit of the orifice;
- Indication of whether the flow is or is not choked;
- Identification of the phases present at sections 1 and 2 as compressed liquid, saturated liquid, or two-phase (liquid-and-vapor).

The relationship between the pressure in the stagnant region, P_s , and the downstream pressure, P_2, is given for a particular set of conditions in Table 1 and in Fig. 12. With reference to Table 1, the four chosen examples correspond to the earlier cited cases as follows:

- Example 1: Case (b), Fig. 3
- Example 2: Case (a), Fig. 3
- Example 3: Case (c), Fig. 3
- Example 4: Case (e), Fig. 3.

Examples 1 and 3 are illustrated graphically in Fig. 12 where P_s and P_2 have been normalized with respect to the stagnation pressure, P_o.

Acknowledgements

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TABLE 1

Relationship Between P_s and P_2 for Refrigerant 114

for Orifice Diameter = 31.75 mm and Pipe Diameter = 50.8 mm

Example 1: $T_o = 30^{o}C$, $P_o = 300$ kPa, $\bar{M} > 1$

Fluid flashes and chokes at (1):

$P_1 = P_s = 250.001$ kPa

$P_2 = 273.804$ kPa

$P_s/P_o = 0.8333$

$P_2/P_o = 0.9127$.

- Fluid flashes at (2) :

$P_s = 210.968$ kPa

$P_2 = 250.225$ kPa

$P_s/P_o = 0.7032$

$P_2/P_o = 0.8341$.

Example 2: $T_o = 30^{o}C$, $P_o = 270$ kPa, $\bar{M} = 1$

- Fluid flashes and chokes at (1) :

$P_1 = P_s = 248.3$ kPa

$P_2 = 259.6$ kPa

$P_s/P_o = 0.920$

$P_2/P_o = 0.962$.

- Fluid flashes at (2) :

$P_s = 231.7$ kPa

$P_2 = 249.3$ kPa

$P_s/P_o = 0.858$

$P_2/P_o = 0.923$.

(continued)

TABLE 1 (continued)

Example 3: $T_o = 30^oC$, $P_o = 255$ kPa, $\bar{M} < 1$

- Fluid flashes at 1 :

  $P_1 = P_s = 250.008$ kPa

  $P_2 = 252.385$ kPa

  $P_s/P_o = 0.9804$

  $P_2/P_o = 0.9897$.

- Fluid flashes at 2 :

  $P_1 = P_s = 245.757$ kPa

  $P_2 = 250.032$ kPa

  $P_s/P_o = 0.9638$

  $P_2/P_o = 0.9805$.

- Fluid chokes at 1 :

  $P_1 = P_s = 242.619$ kPa

  $P_2 = = 247.827$ kPa

  $P_s/P_o = 0.9514$

  $P_2/P_o = 0.9719$.

Example 4: $T_o = 30^oC$, $P_o = 200$ kPa, $\bar{M} = 1$

- Fluid flashes before nozzle entrance.
- Fluid chokes at 1 :

  $P_1 = P_s = 155.7$ kPa

  $P_2 = 173.5$ kPa

  $P_s/P_o = 0.778$

  $P_2/P_o = 0.867$.

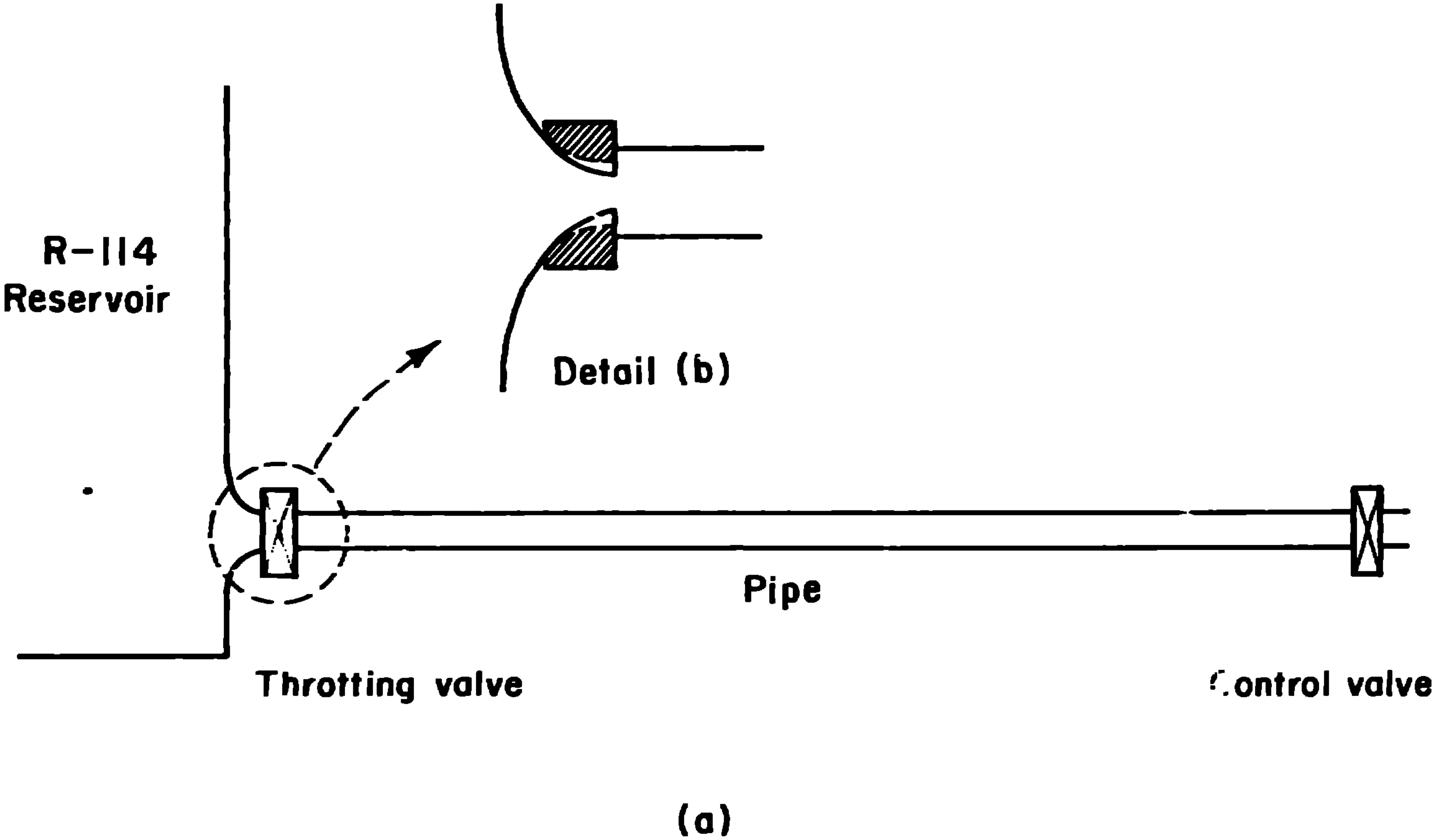


FIGURE 1. SCHEMATIC OF SYSTEM AND ORIFICE.

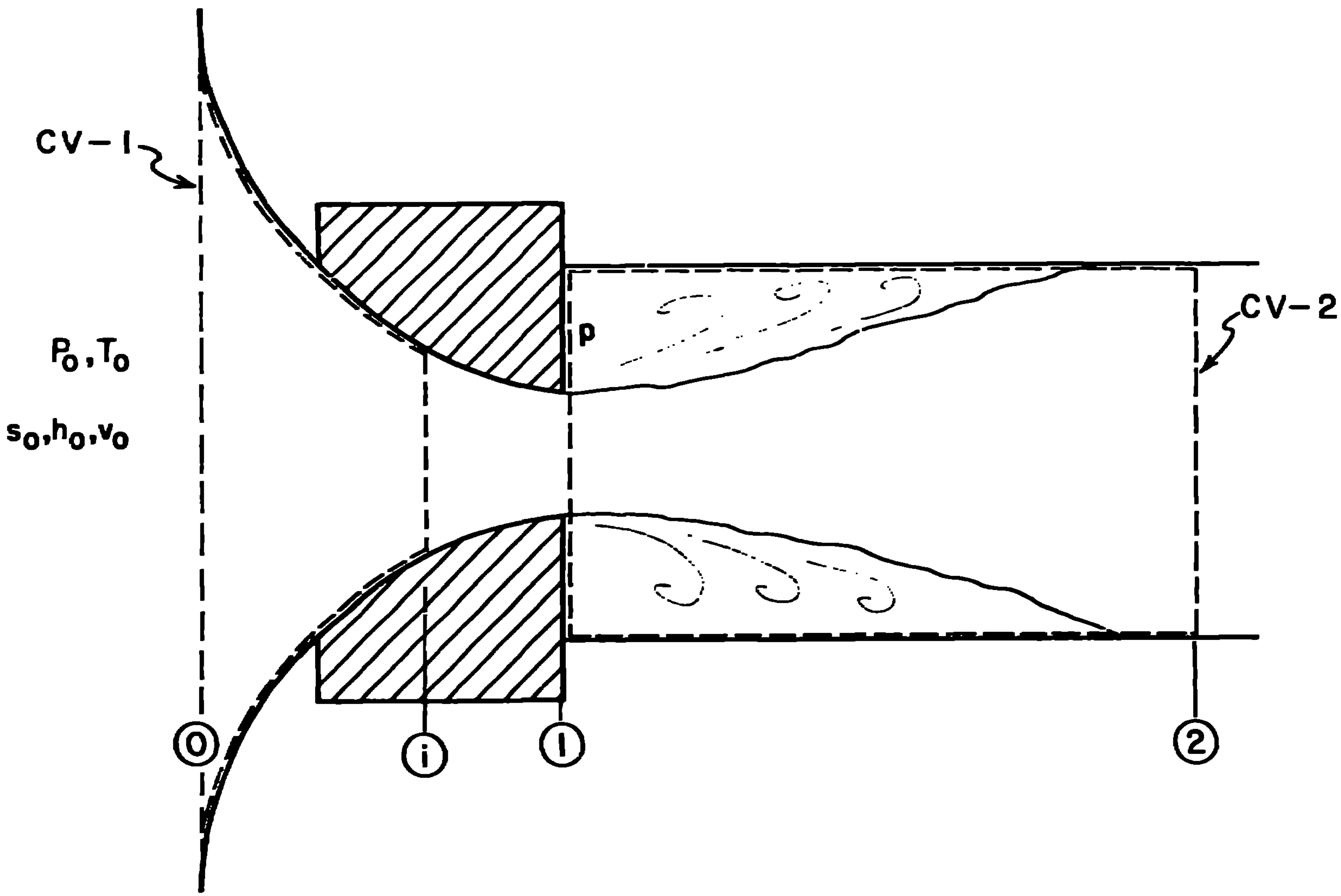


FIGURE 2. FLOW BETWEEN STAGNATION POINT AND ANY OTHER SECTION.

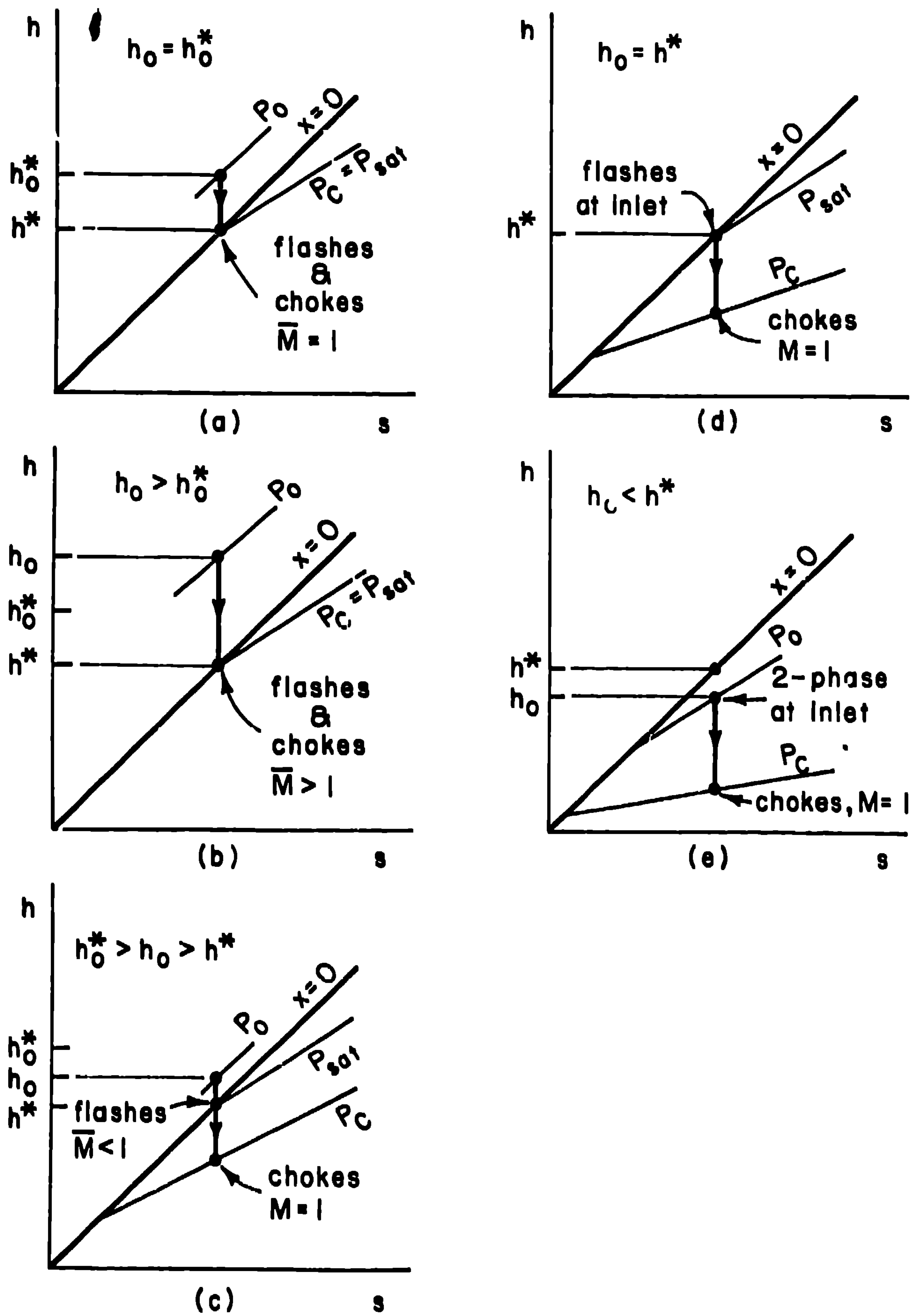


FIGURE 3. MOLLIER DIAGRAMS FOR VARIOUS FLOW PROCESSES.

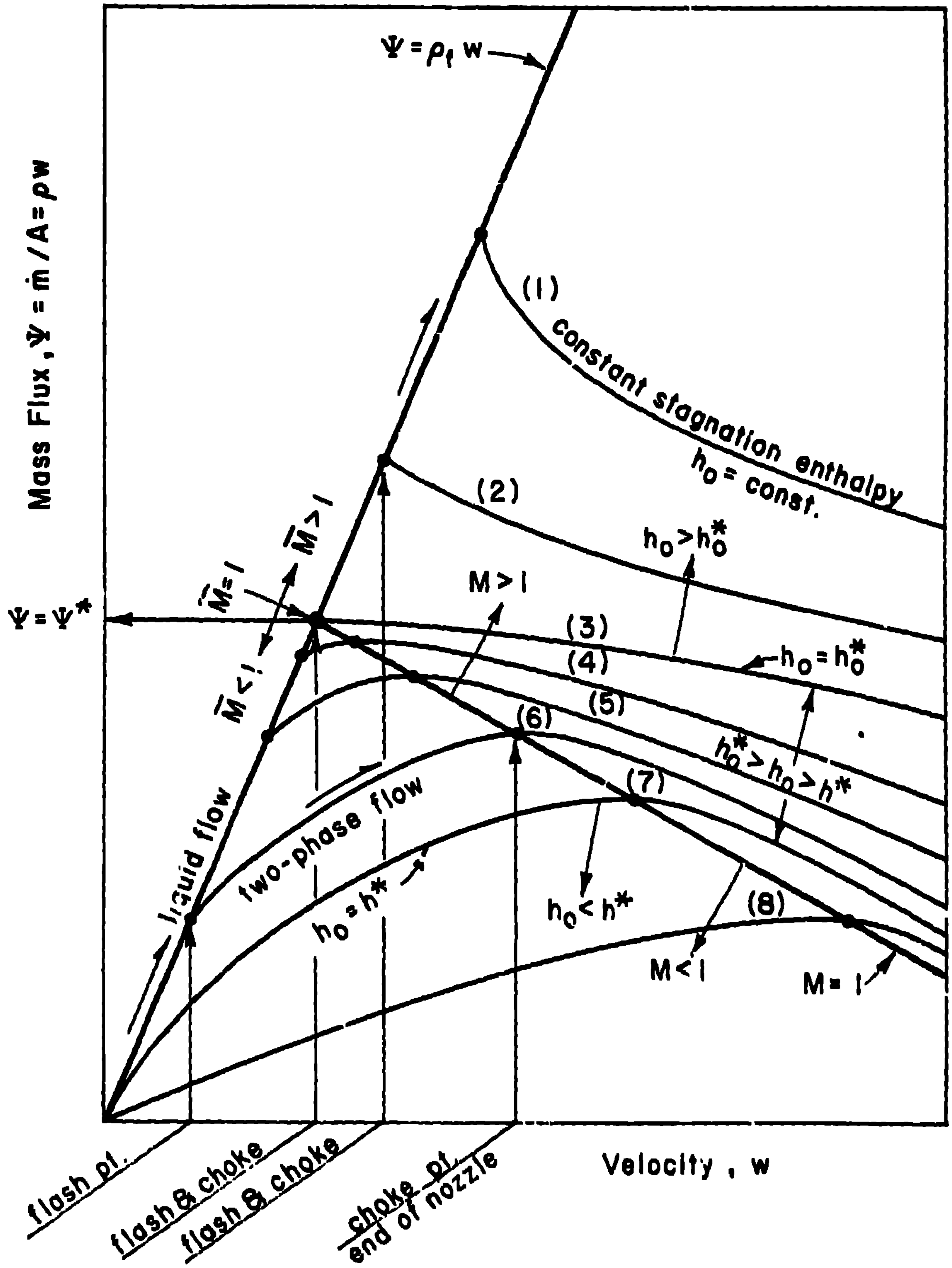
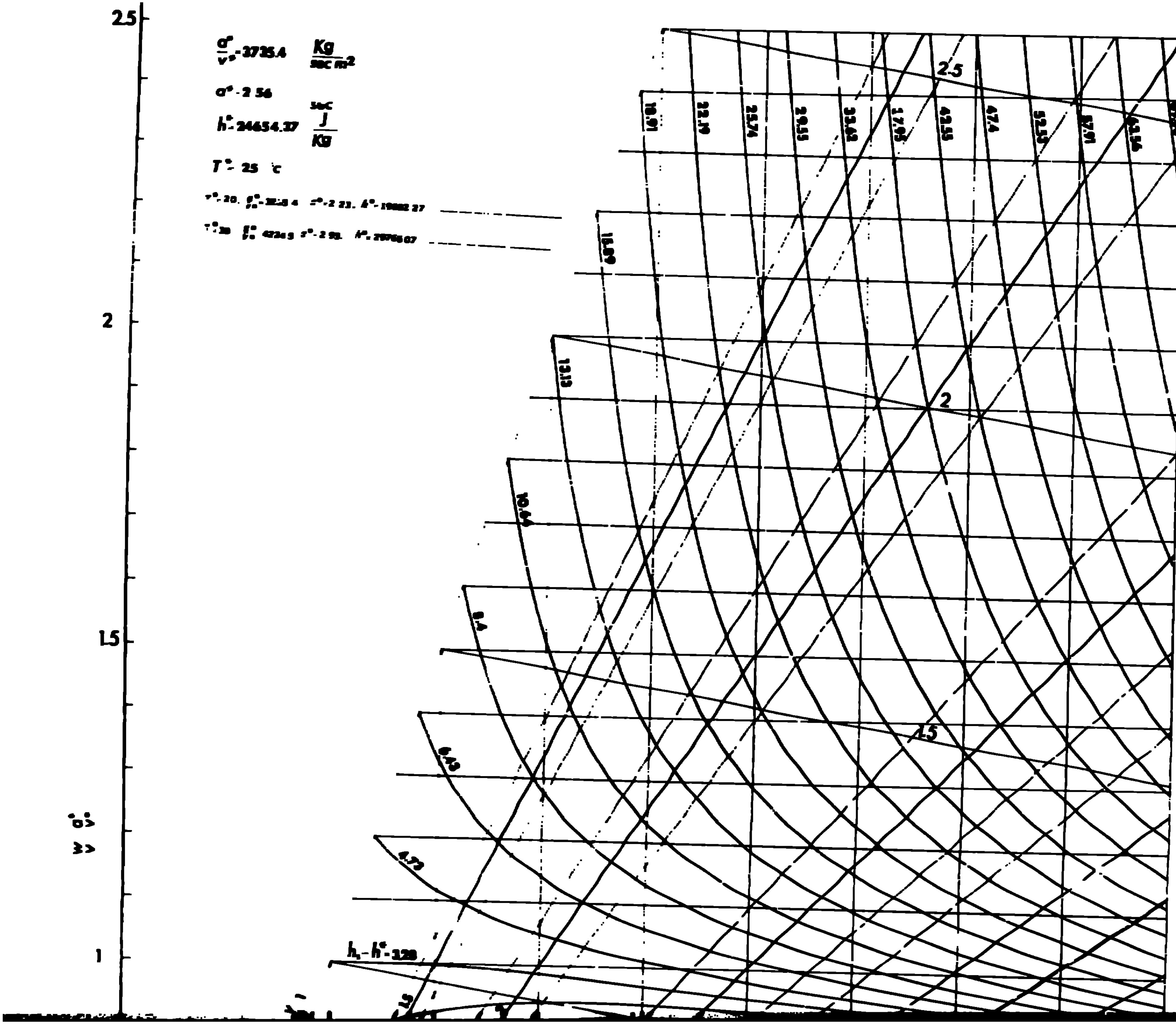


FIGURE 4. SCHEMATIC SHOWING MASS FLUX VERSUS VELOCITY FOR VARIOUS STAGNATION ENTHALPIES.



2.5
2
1.5
1
σ°/v° = 3735.4 Kg/sec m²
σ° = 2 56
h° = 24654.37 J/Kg
T° = 25 °c
2.5
2
1.5
18.91
22.19
25.74
29.55
33.62
43.55
47.4
52.55
57.91
15.69
13.19
10.64
8.4
6.43
4.73
h₁ - h° = 328

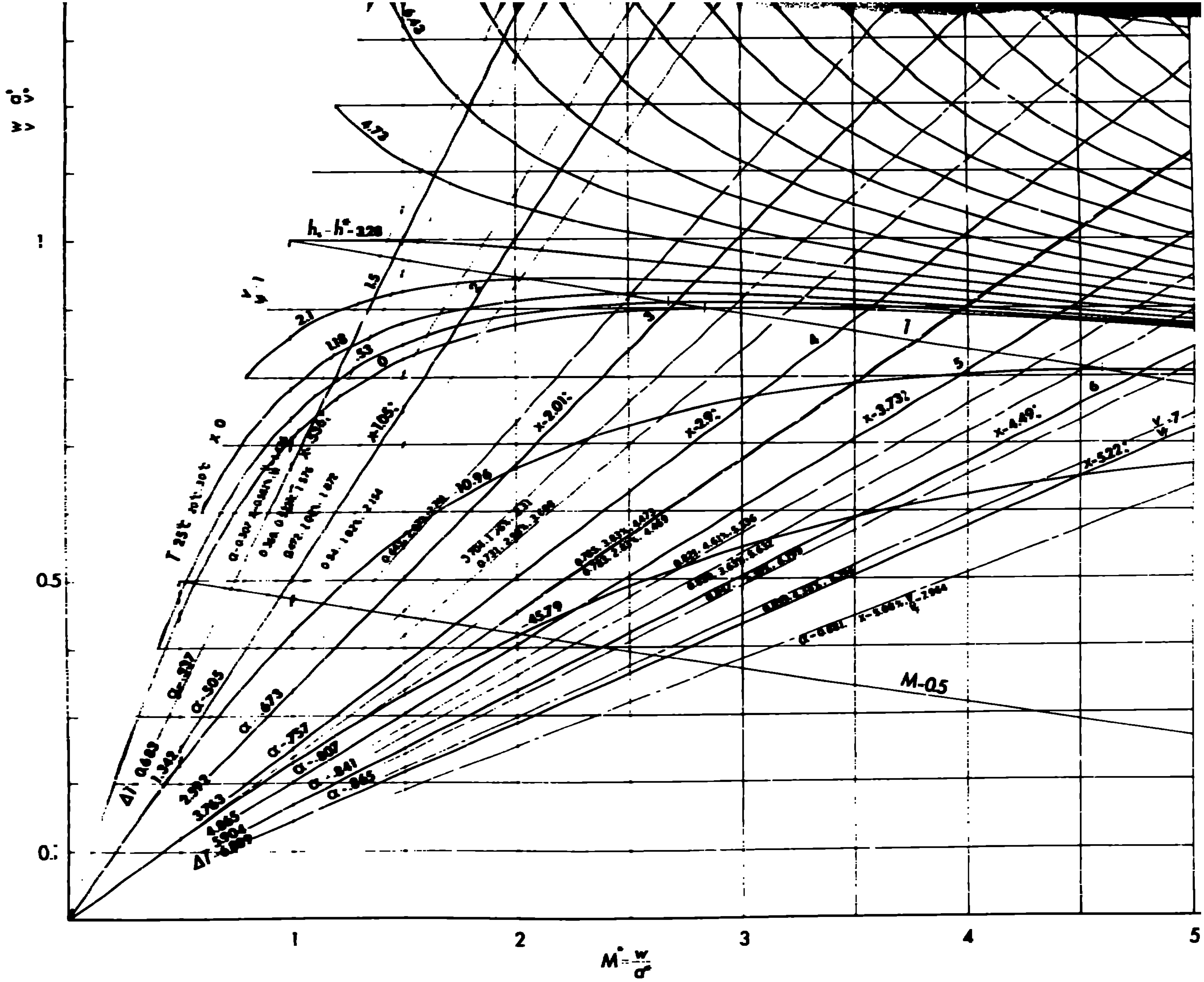


FIGURE 5. NOZZLE PERFORMANCE CURVES FOR R114.

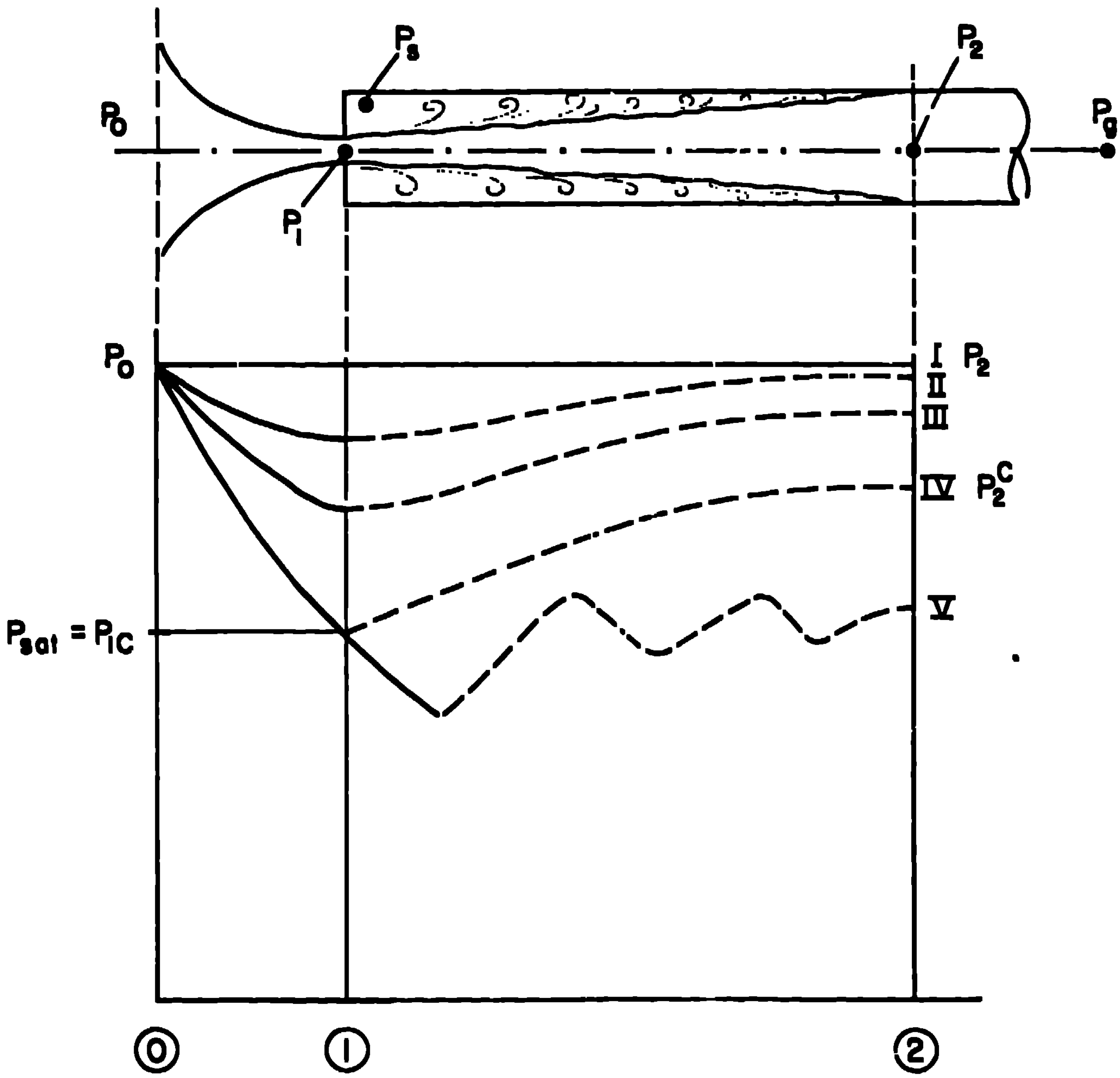


FIGURE 6(A). CENTERLINE PRESSURE FOR VARIOUS BACK PRESSURES: $H_C > H_0$.

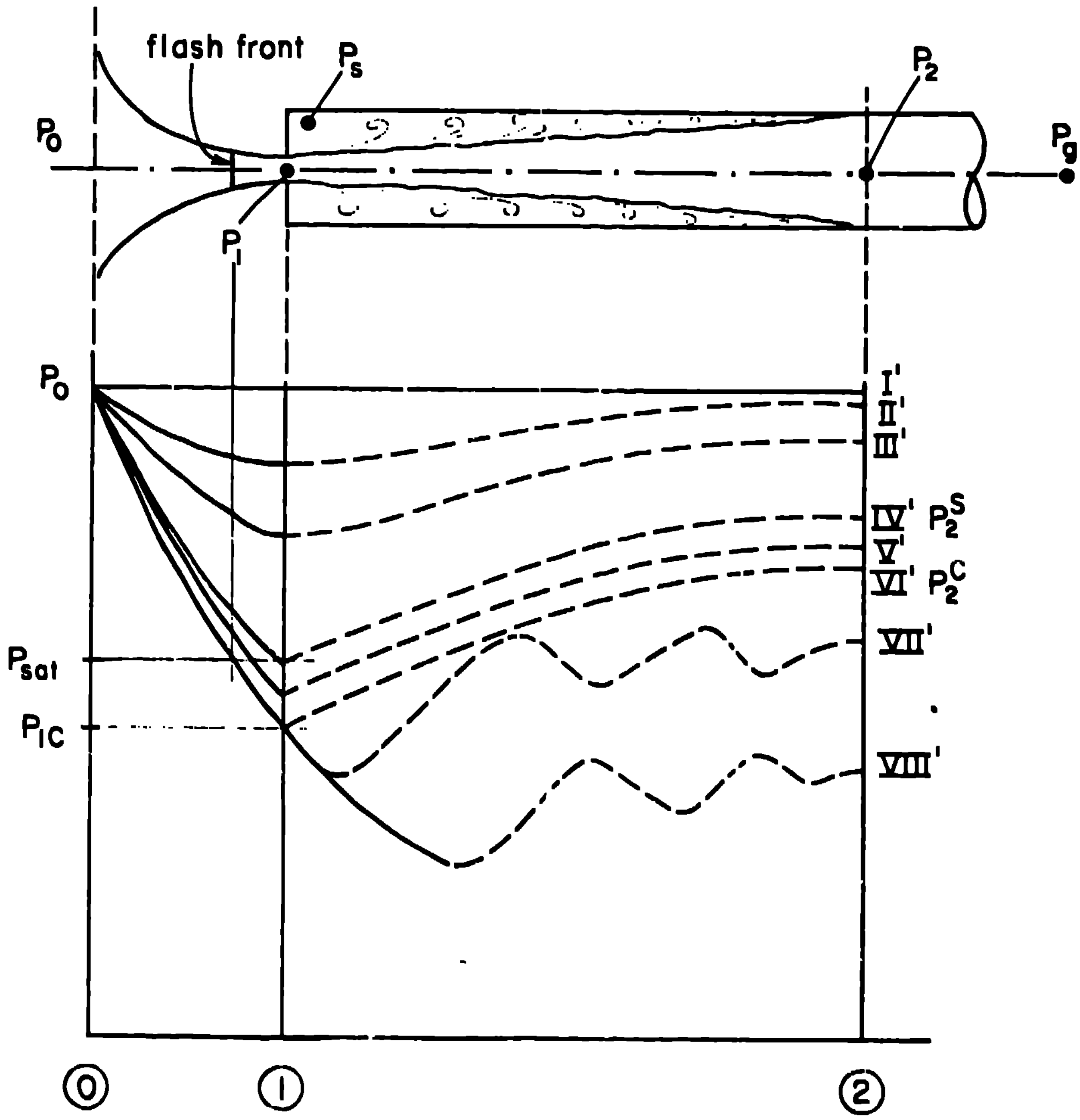


FIGURE 6(B). CENTERLINE PRESSURE FOR VARIOUS BACK PRESSURES: $H^* < H_0 < H_0^*$.

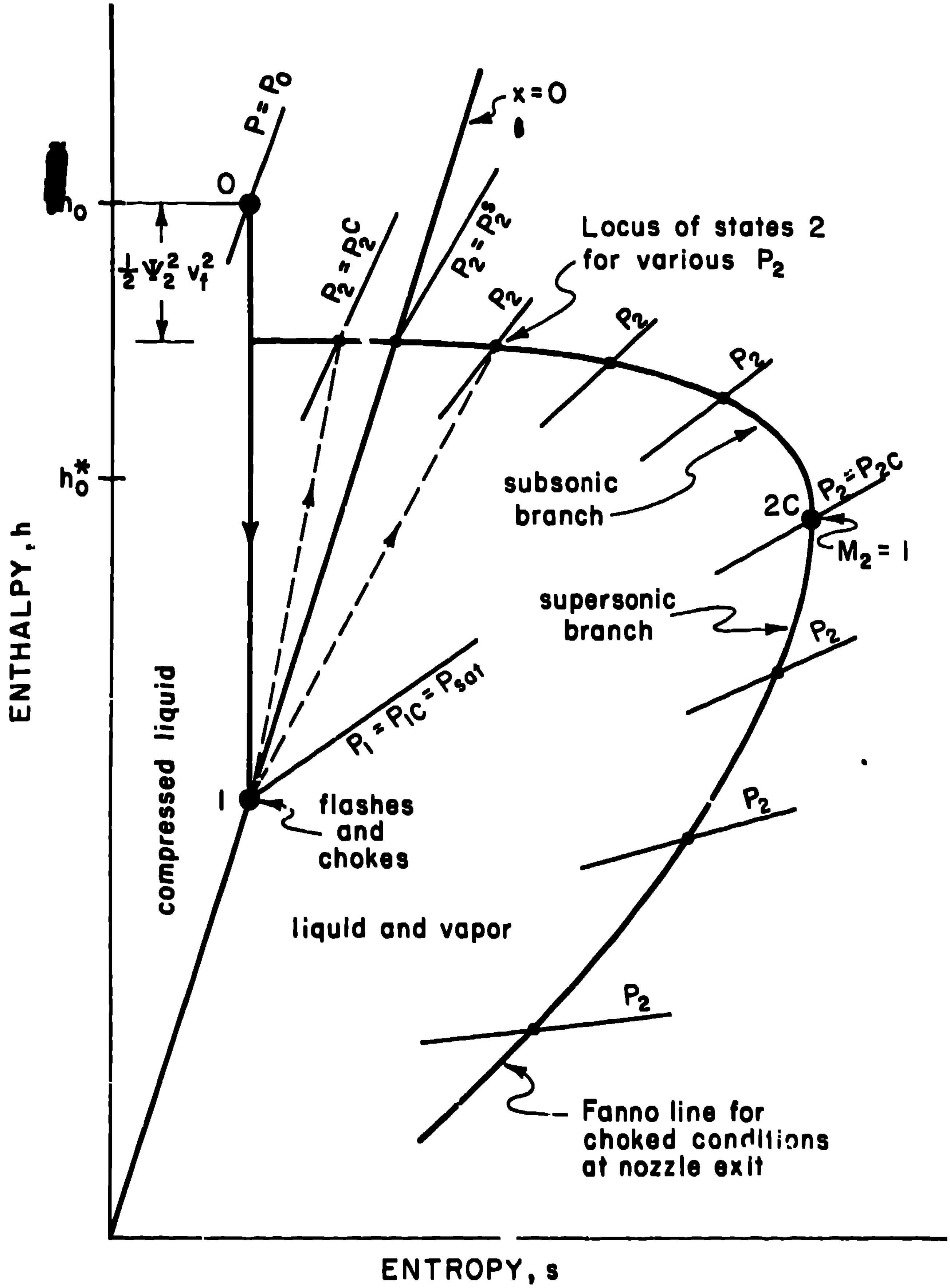


FIGURE 7. FANNO CURVE FOR CHOKED CONDITIONS AT NOZZLE EXIT.

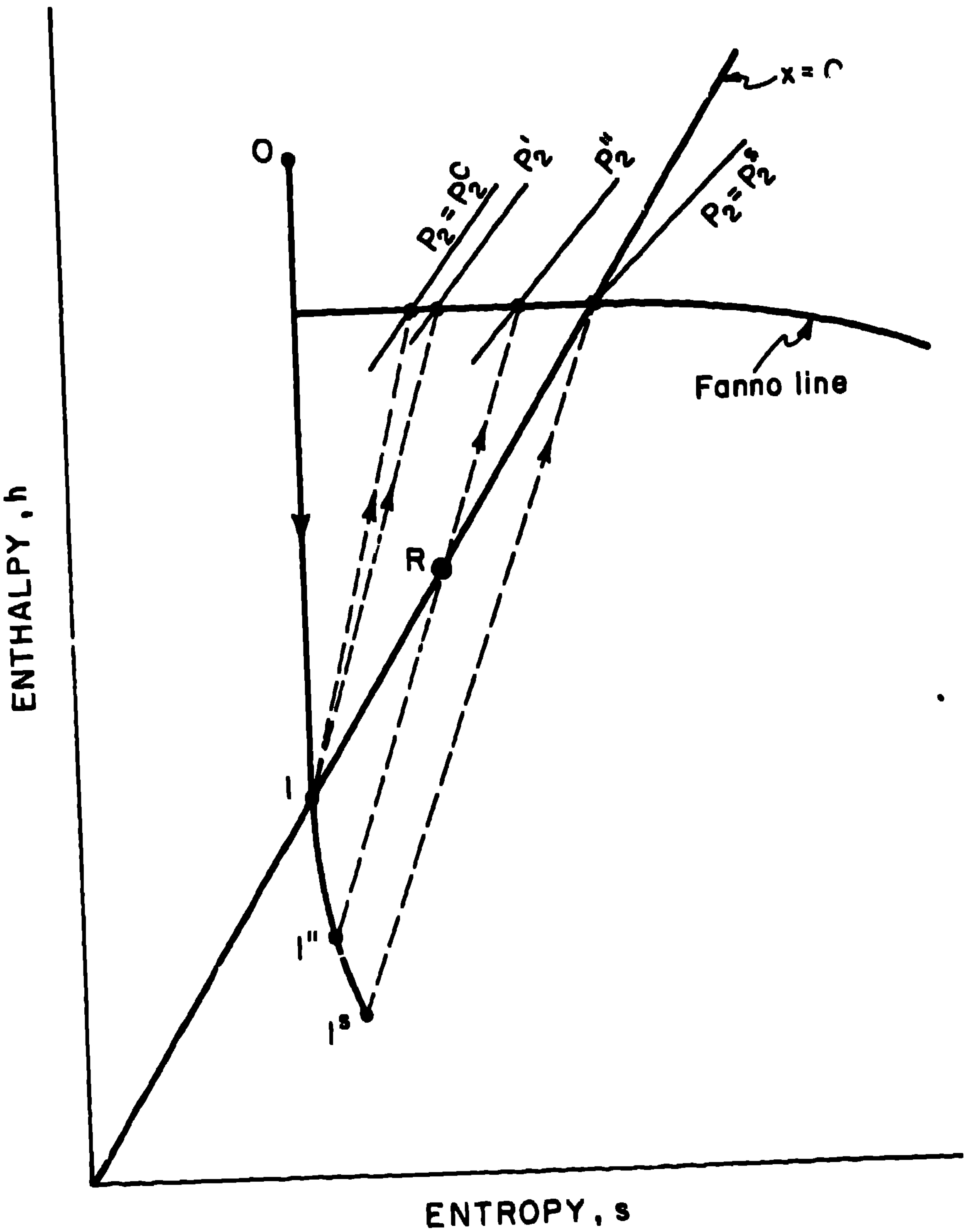


FIGURE 8. NOZZLE PROCESSES ILLUSTRATING JUMP CONDITIONS.

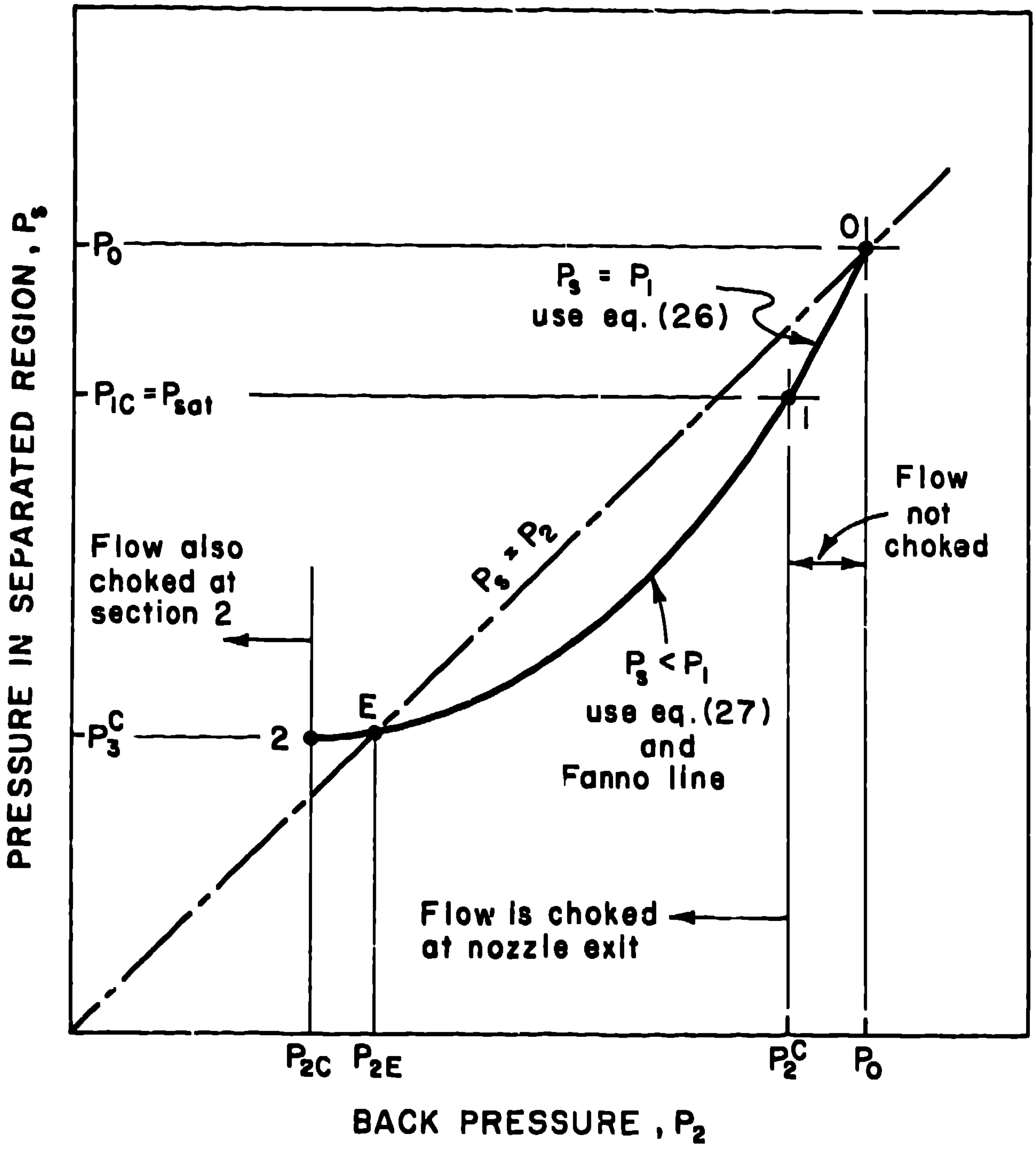


FIGURE 9. RELATIONSHIP BETWEEN PRESSURE IN THE SEPARATED REGION AND BACK PRESSURE.

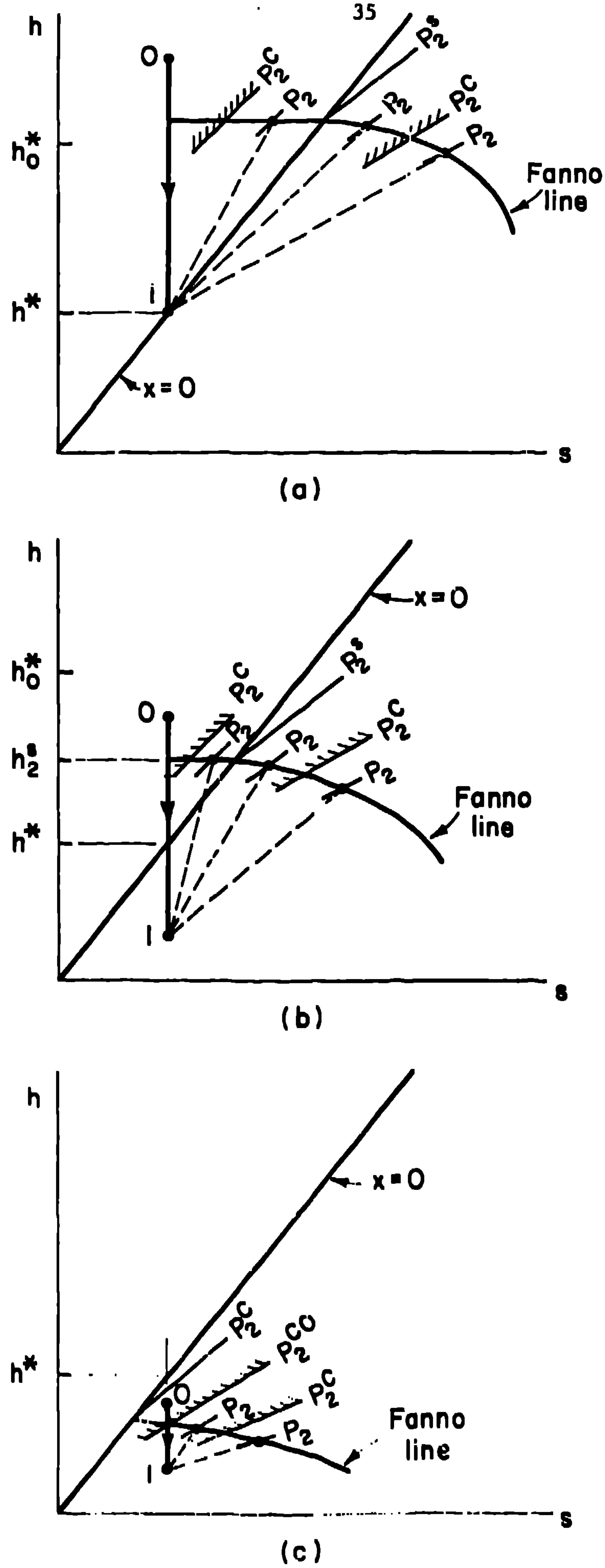


FIGURE 10. SUMMARY OF FLOW CONDITIONS WHEN FLOW IS CHOKED AT NOZZLE EXIT.

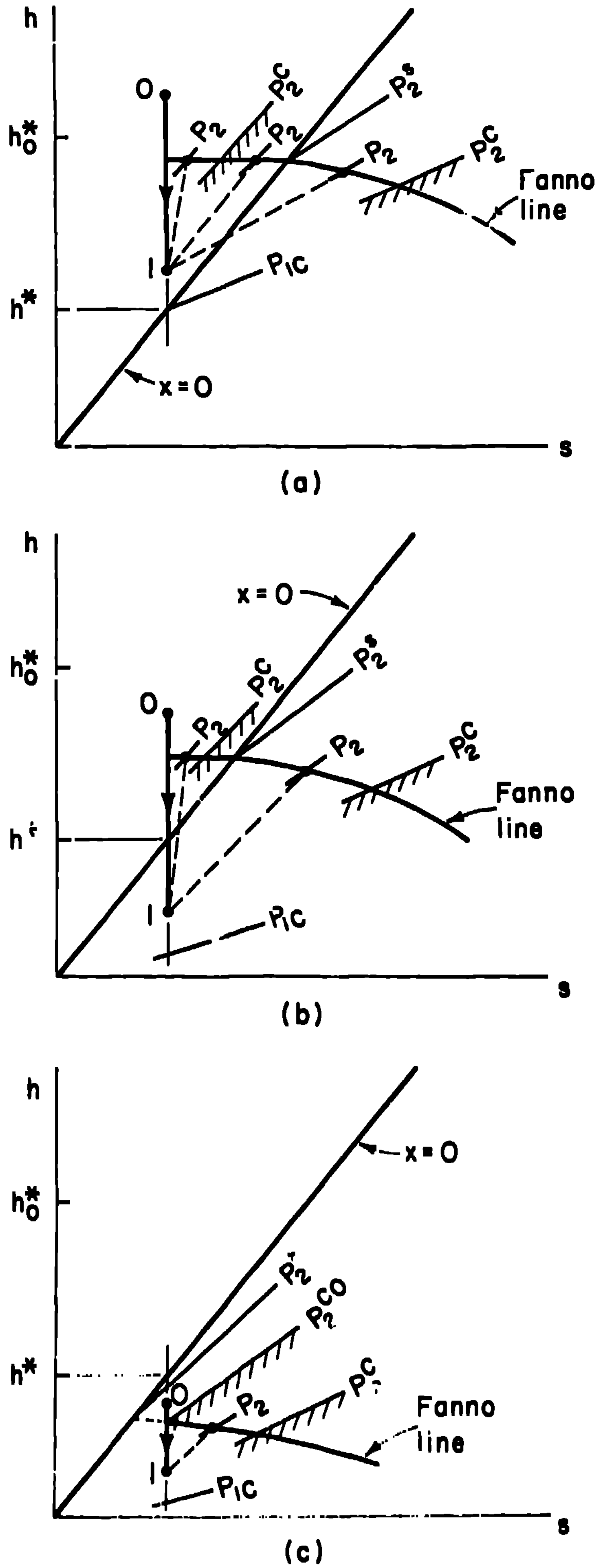


FIGURE 11. SUMMARY OF FLOW CONDITIONS WHEN FLOW IS NOT CHOKED AT NOZZLE EXIT.

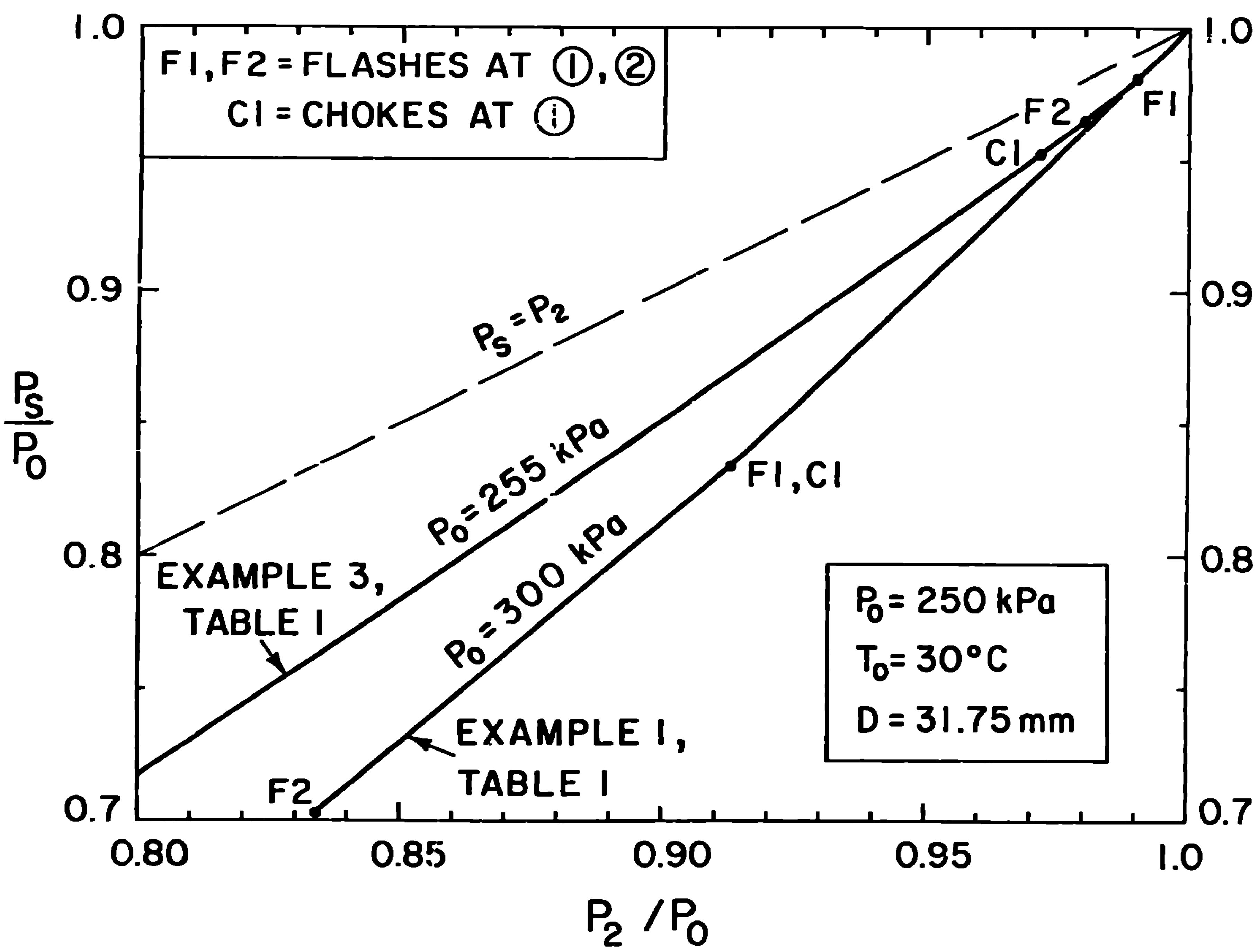


FIGURE 12. SAMPLE RESULTS FOR R114.

APPENDIX

FLOW CALCULATION PROGRAM

Coded in BASIC for use with

Hewlett Packard Model HP-85 computer

RF:JET

```
10 ! Flow in an Orifice and its
   expansion into a pipe.
20 ! Entropy production's calcu
   lation as a function of pres
   sure in seperated region
30 ! Working fluid is FREON 114
   .Reservoir,orifice exit and
   downstream flow are denoted
   by 0,1,2
40 ! pressure in separated regi
   on is given by P.P3 correspo
   nds to sat. condition at 2
50 ! The numbers 1,2 and 3 in b
   racets correspond to flash p
   oint,cond. at 1 when flow at
    2 is.
60 ! saturated and choking cond
   ition.Exception P0(3),T0(3)
   stands for sat. conditions a
   t 2.
70 OPTION BASE 1@ CLEAR
80 COM Y(10),U1$[20],U2$[20],U$
   [20] ,INTEGER I,N
90 FOR N=1 TO 6 @ Y(N)=1 @ NEXT
    N @ I=12
100 A$="Subchoked flow" @ B$="Ch
   oked flow" @ C$="P1=" @ D$="
   P2=" @ E$="From " @ F$="To "
110 T$="[T]" @ S$="[S]" @ G$="P=
   " @ L$="[L]" @ N$=""
120 ! ******** Input #1 ********
130 DISP "Orifice,pipe diameter
   in inch";@ INPUT J1,J2
140 IF J1=0 THEN CLEAR @ DISP "N
   o flow!" @ GOTO 130
150 DISP "Stag.conditions:Liquid
   ,Saturated or in T-phase reg
   ion:L/S/T";@ INPUT Y$
160 IF Y$="S" OR Y$="T" THEN GOT
   O 200
170 DISP "Stag.conditions,P=?,T=
   ?:Kpa,C";@ INPUT U1$,U2$@ I=
   23
180 IF U1$[1,1]#"P" THEN 170
190 IF U2$[1,1]#"T" THEN 170 ELS
   E Y(3)=VAL(U1$[3]) @ Y(2)=VA
   L(U2$[3]) @ DISP "WAIT!" @ G
   OTO 2260
200 IF Y$="T" THEN GOTO 240
210 DISP "Stag.conditions,x=?,s=
   ? ,KJ/Kg";@ INPUT U1$,U2$@
   I=15
220 IF U1$[1,1]#"x" THEN 210
230 IF U2$[1,1]#"s" THEN 210 ELS
   E Y(1)=VAL(U1$[3]) @ Y(5)=VA
   L(U2$[3]) @ DISP "WAIT!" @ G
   OTO 2260
240 DISP "Stag.condition,P=?,s=?
   :Kpa,KJ/Kg";@ INPUT U1$,U2$@
    I=35
250 IF U1$[1,1]#"P" THEN 240
260 IF U2$[1,1]#"s" THEN 240 ELS
   E Y(3)=VAL(U1$[3]) @ Y(5)=VA
   L(U2$[3]) @ DISP "WAIT!" @ G
   OTO 2260
270 ! ******** Output #2 *******
280 PRINT TAB(12);U$ @ PRINT TAB
   (12);D$;Y(3) @ GOTO 300
290 PRINT TAB(12);G$;P @ PRINT T
   AB(12);U$ @ GOTO 300
300 PRINT TAB(12);"s2=";Y(5) @ P
   RINT @ CLEAR @ PRINT @ PRINT
    @ GOTO 330
310 ! ******** Input #2 ********
320 PRINT @ GOSUB 4370 @ CLEAR
330 P1=0 @ P2=0 @ P=0 @ F0=0 @ Y
   (3)=0 @ Y(5)=0 @ DISP "Subch
   oked:Orifice exitpress.P1=?"
    @ DISP
340 DISP "Choked:Downstream pres
   s.P2=?" @ DISP
350 DISP "Enter proper pressure"
   ;@ INPUT U$@ IF U$="" THEN 3
   30
360 IF U$[1,2]="P1" OR U$[1,2]="
   P2" THEN 370 ELSE 330
370 IF U$[1,2]="P1" THEN P1=VAL(
   U$[4]) @ F0=1 ELSE 390
380 IF P1<P1(3) OR P1>P0 THEN CL
   EAR @ DISP "Out of range!" @
    GOTO 330 ELSE 400
390 P2=VAL(U$[4]) @ F0=2 @ IF P2
   >P2(3) THEN CLEAR @ DISP "Ou
   t of range!" @ GOTO 330
400 ON F GOTO 410,420,430
410 ON F1 GOTO 440,540,610
420 ON F1 GOTO 710,?30,1060
430 GOTO 1210
440 IF F0=1 THEN GOTO 450 ELSE 5
   10
450 GOTO 1290
460 IF P1=P1(2) THEN Y(3)=P0(2)
   @ Y(5)=S0(2) @ GOTO 280
470 IF P1>P1(2) THEN GOSUB 3510
   ELSE 490
480 GOTO 280
490 IF P1<P1(2) THEN GOSUB 3630
500 GOTO 280
510 GOTO 1360
520 IF P2<P2(3) THEN GOSUB 3770
530 GOTO 290
540 IF F0=1 THEN 550 ELSE 580
550 GOTO 1290
560 IF P1>P1(3) THEN GOSUB 3510
570 GOTO 280
580 GOTO 1360
590 IF P2<P2(3) THEN GOSUB 3770
600 GOTO 290
610 IF F0=1 THEN 620 ELSE 650
620 GOTO 1290
```

```
630 IF P1>P1(3) THEN GOSUB 3510
640 GOTO 280
650 GOTO 1360
660 IF P2=P0(3) THEN P=P3 @ Y(5)
    =S0(3) @ GOTO 290
670 IF P2>P0(3) AND P2<P2(3) THE
    N GOSUB 3810 ELSE 690
680 GOTO 290
690 IF P2<P0(3) THEN GOSUB 3770
700 GOTO 290
710 IF F0=1 THEN 720 ELSE 950
720 ON F2 GOTO 730,820,880
730 GOTO 1290
740 IF P1=P1(1) THEN Y(3)=P2(1)
    @ Y(5)=S2(1) @ GOTO 280
750 IF P1=P1(2) THEN Y(3)=P0(2)
    @ Y(5)=S0(2) @ GOTO 280
760 IF P1>P1(1) THEN GOSUB 3510
    ELSE 780
770 GOTO 280
780 IF P1>P1(2) AND P1<P1(1) THE
    N GOSUB 3560 ELSE 800
790 GOTO 280
800 IF P1<P1(2) THEN GOSUB 3630
810 GOTO 280
820 GOTO 1290
830 IF P1=P1(1) THEN Y(3)=P0(2)
    @ Y(5)=S0(2) @ GOTO 280
840 IF P1>P1(1) THEN GOSUB 3510
    ELSE 860
850 GOTO 280
860 IF P1<P1(1) THEN GOSUB 3630
870 GOTO 280
880 GOTO 1290
890 IF P1=P1(2) THEN Y(3)=P0(2)
    @ Y(5)=S0(2) @ GOTO 280
900 IF P1=P1(1) THEN Y(3)=P2(1)
    @ Y(5)=S2(1) @ GOTO 280
910 IF P1>P1(2) THEN GOSUB 3510
    ELSE 930
920 GOTO 280
930 IF P1<P1(2) THEN GOSUB 3630
940 GOTO 280
950 GOTO 1360
960 IF P2<P2(3) THEN GOSUB 3770
970 GOTO 290
980 IF F0=1 THEN 990 ELSE 1050
990 GOTO 1290
1000 IF P1=P1(1) THEN Y(3)=P2(1)
     @ Y(5)=S2(1) @ GOTO 280
1010 IF P1>P1(1) THEN GOSUB 3510
     ELSE 1030
1020 GOTO 280
1030 IF P1<P1(1) THEN GOSUB 3560
1040 GOTO 280
1050 GOTO 1360
1060 IF P2<P2(3) THEN GOSUB 3770
1070 GOTO 290
1080 IF F0=1 THEN 1090 ELSE 1150
1090 GOTO 1290
1100 IF P1=P1(1) THEN Y(3)=P2(1)
     @ Y(5)=S2(1) @ GOTO 280
1110 IF P1>P1(1) THEN GOSUB 3510
     ELSE 1130
1120 GOTO 280
1130 IF P1<P1(1) THEN GOSUB 3560
1140 GOTO 280
1150 GOTO 1360
1160 IF P2=P0(3) THEN P=P3 @ Y(5
     )=S0(3) @ GOTO 290
1170 IF P2>P0(3) AND P2<P2(3) TH
     EN GOSUB 3810 ELSE 1190
1180 GOTO 290
1190 IF P2<P0(3) THEN GOSUB 3770
1200 GOTO 290
1210 IF F0=1 THEN 1220 ELSE 1250
1220 GOTO 1290
1230 IF P1>P1(3) THEN GOSUB 3630
1240 GOTO 280
1250 GOTO 1360
1260 IF P2<P2(3) THEN GOSUB 3770
1270 GOTO 290
1280 ! Subroutine for output #2
     *************/************.
1290 IF P1=P0 THEN Y(3)=P0 @ Y(5
     )=S0 @ GOTO 280
1300 IF P1=P1(3) THEN Y(3)=P2(3)
     @ Y(5)=S2(3) @ GOTO 280
1310 ON F GOTO 1320,1330,1350
1320 ON F1 GOTO 460,560,630
1330 ON F1 GOTO 1340,1000,1100
1340 ON F2 GOTO 740,830,890
1350 GOTO 1230
1360 IF P2=P2(3) THEN P=P1(3) @
     Y(5)=S2(3) @ GOTO 290
1370 IF P2=P2(4) THEN P=P4 @ Y(5
     )=S0 @ GOTO 290
1380 ON F GOTO 1390,1400,1410
1390 ON F1 GOTO 520,590,660
1400 ON F1 GOTO 960,1060,1160
1410 GOTO 1260
1420 ! *** Equation of state ***
1430 DISP "NOT AVAILABLE!;S erh
     eated vapor" @ STOP
1440 DISP "Compressed liquid! In
     put P,T =";@ STOP
1450 Y(16)=FNF1(Y(2))
1460 Y(11)=SQR(1000*FNH2(Y(2)))
1470 Y(14)=Y(6)*FNP2(Y(2))/FNP6(
     Y(2))
1480 Y(12)=Y(14)/SQR(Y(16)+Y(1)*
     FNH2(Y(2)))
1490 Y(7)=Y(12)*Y(11)
1500 Y(8)=Y(7)/Y(6)
1510 Y(10)=(FNP6(Y(2))/Y(3)+FNV1
     (Y(2)))*Y(1)/Y(6)
1520 RETURN
1530 IF IP(I/10)>1@*FP(I/10) THE
     N I=IP(I/10)+100*FP(I/10)
1540 IF I=12 THEN 1620
```

```
1550 IF I=23 THEN 1710
1560 N=I-12 @ IF N<5 THEN 1600
1570 N=N-6 @ IF N<9 THEN 1600
1580 N=N-7 @ IF N<12 THEN 1600
1590 N=N-8 @ IF N>17 THEN N=14
1600 ON N GOSUB 2000,1680,1690,1
     700,1560,1770,1780,1790,180
     0,1820,1840,1860,1880,1900
1610 DEF FNN(N) = FP(I/10)*10#N
     AND IP(I/10)#N
1620 IF FNN(3) THEN Y(3)=FNP2(Y(
     2))
1630 IF FNN(4) THEN Y(4)=FNH(Y(2
     ))
1640 IF FNN(5) THEN Y(5)=FNS(Y(2
     ))
1650 IF FNN(6) THEN Y(6)=FNV(Y(2
     ))
1660 IF Y(1)<0 THEN 1440
1670 IF Y(1)>1 THEN 1430 ELSE RE
     TURN
1680 G=Y(4) @ B=FNH(Y(2)) @ C=FN
     H(Y(2)+.5) @ A=FNH(Y(2)-.5)
      @ GOSUB 1990 @ IF N THEN 1
     680 ELSE RETURN
1690 G=Y(5) @ B=FNS(Y(2)) @ C=FN
     S(Y(2)+.5) @ A=FNS(Y(2)-.5)
      @ GOSUB 1990 @ IF N THEN 1
     690 ELSE RETURN
1700 G=Y(6) @ B=FNV(Y(2)) @ C=FN
     V(Y(2)+.5) @ A=FNV(Y(2)-.5)
      @ GOSUB 1990 @ IF N THEN 1
     700 ELSE RETURN
1710 IF Y(3)<FNP2(Y(2)) THEN 143
     0
1720 Y(6)=FNV1(Y(2))*FNV2(Y(3))
1730 Y(4)=Y(6)*(Y(3)-FNP2(Y(2)))
1740 Y(5)=Y(4)*(-.00000025)*Y(3)
     /(273+Y(2))
1750 Y(4)=Y(4)+FNH1(Y(2))*(1-.00
     00007*Y(3)) @ Y(5)=(Y(5)+FN
     S1(Y(2)))*(1-.0000007*Y(3))
1760 RETURN
1770 Y(1)=FNX4(Y(2)) @ RETURN
1780 Y(1)=FNX5(Y(2)) @ RETURN
1790 Y(1)=FNX6(Y(2)) @ RETURN
1800 GOSUB 2000
1810 GOTO 1770
1820 GOSUB 2000
1830 GOTO 1780
1840 GOSUB 2000
1850 GOTO 1790
1860 G=Y(4) @ Y(1)=FNX5(Y(2)-.5)
      @ A=FNH(Y(2)-.5) @ Y(1)=FN
     X5(Y(2)+.5) @ C=FNH(Y(2)+.5
     )
1870 Y(1)=FNX5(Y(2)) @ B=FNH(Y(2
     )) @ GOSUB 1990 @ IF N THEN
      1860 ELSE RETURN
1880 G=Y(4) @ Y(1)=FNX6(Y(2)-.5)
      @ A=FNH(Y(2)-.5) @ Y(1)=FN
     X6(Y(2)+.5) @ C=FNH(Y(2)+.5
     )
1890 Y(1)=FNX6(Y(2)) @ B=FNH(Y(2
     )) @ GOSUB 1990 @ IF N THEN
      1880 ELSE RETURN
1900 G=Y(5) @ Y(1)=FNX6(Y(2)-.5)
      @ A=FNS(Y(2)-.5) @ Y(1)=FN
     X6(Y(2)+.5) @ C=FNS(Y(2)+.5
     )
1910 Y(1)=FNX6(Y(2)) @ B=FNS(Y(2
     )) @ GOSUB 1990 @ IF N THEN
      1900 ELSE RETURN
1920 !  SUBROUTINES
1930 DEF FNH(T) = FNH1(T)+Y(1)*F
     NH2(T)
1940 DEF FNX4(T) = (Y(4)-FNH1(T)
     )/FNH2(T)
1950 DEF FNS(T) = FNS1(T)+Y(1)*F
     NH2(T)/(273+T)
1960 DEF FNX5(T) = (T+273)*(Y(5)
     -FNS1(T))/FNH2(T)
1970 DEF FNV(T) = FNV1(T)*FNV2(Y
     (3))+Y(1)*FNP6(T)/Y(3)
1980 DEF FNX6(T) = FNP2(T)*(Y(6)
     -FNV1(T))/FNP6(T)
1990 D=(G-B)/(C-A) @ Y(2)=Y(2)+D
      @ N=ABS(D)>.01 @ RETURN
2000 G=LOG(Y(3)) @ B=LOG(FNP2(Y(
     2))) @ C=LOG(FNP2(Y(2)+.5))
      @ A=LOG(FNP2(Y(2)-.5)) @ G
     OSUB 1990
2010 IF N THEN 2000 ELSE RETURN
2020 DEF FNF1(T) = (FNS1(T+.5)-(
     FNS1(T-.5)))*(T+273.15)^2/F
     NH2(T)
2030 DEF FNF2(T)
2040 F2=(FNH2(T+.5))*(FNP6(T-.5)
     )*(FNP2(T+.5))*(T+272.65)
2050 F2=F2/(FNH2(T-.5))/(FNP6(T+
     .5))/(FNP2(T-.5))/(T+273.65
     )
2060 FNF2=(T+273.15)*LOG(F2)
2070 FN END
2080 ! ************************
2090 ! POLYNOMIALS FOR RF114
2100 ! ************************
2110 ! h(f)
2120 DEF FNH2(T) = ((T*-.0000024
     402-.0011455[illegible])*T-.3315[illegible]
     5)*T+132.40[illegible]
2130 ! P*v(f)
2140 DEF FNP6(T) = (((T*-.000000
     0033-1.16291[illegible])*T-.000[illegible]
     073[illegible])*T+.0304[illegible]01443)*T+1
     2.7532170[illegible]
2150 ! P
2160 DEF FNP2(T) = 10^((T*.00000
     0407-.00497495[illegible])*T+7.92[illegible]
     665-1649.100/(T+273.15))
2170 ! h(l)
2180 DEF FNH1(T) = ((T*-.0000012
     4122+.00127263[illegible])*T+.955[illegible]
     )*T
```

```
2190 ! s(l)
2200 DEF FNS1(T) = ((T*-1.62754E
     -8+.0000491732)*T-.0001768
     4)*T+LOG(T/273+1)
2210 ! v(l)
2220 DEF FNV1(T) = ((T*3.4858654
     E-11+3.6841033E-9)*T+.00000
     1192772)*T+6.539242079E-4
2230 ! Compressibility of liquid
2240 DEF FNV2(P) = 1-.000004336*
     P
2250 ! ******* Output #1 *******
2260 A1=FNA(J1) @ A2=FNA(J2) @ G
     OSUB 1530
2270 PRINT TAB(8);"Orifice=";J1;
     "in" @ PRINT TAB(8);"Pipe="
     ;J2;"in" @ PRINT @ GOSUB 43
     70
2280 T0=Y(2) @ P0=Y(3) @ H0=Y(4)
      @ S0=Y(5) @ V0=Y(6) @ PRIN
     T TAB(8);"Stag.conditions"
     @ PRINT
2290 PRINT TAB(8);"P0=";P0 @ PRI
     NT TAB(8);"T0=";T0 @ PRINT
     TAB(8);"h0=";H0
2300 PRINT TAB(8);"s0=";S0 @ PRI
     NT TAB(8);"v0=";V0 @ PRINT
     @ GOSUB 4370
2310 IF Y$="S" OR Y$="T" THEN 32
     40 ELSE Y(1)=0 @ Y(5)=S0 @
     I=15 @ GOSUB 1530
2320 GOSUB 1450
2330 T1(1)=Y(2) @ P1(1)=Y(3) @ H
     1(1)=Y(4) @ V1(1)=Y(6) @ W0
     =Y(7)
2340 PRINT TAB(5);"Flash point c
     onditions" @ PRINT @ PRINT
     TAB(8);"Pf=";P1(1)
2350 PRINT TAB(8);"Tf=";T1(1) @
     PRINT TAB(8);"hf=";H1(1) @
     PRINT TAB(8);"sf=";S0
2360 PRINT TAB(8);"vf=";V1(1) @
     PRINT @ GOSUB 4370
2370 Y(1)=0 @ Y(4)=P0 @ I=14 @ G
     OSUB 1530
2380 P0(9)=Y(3) @ W1(1)=FNW(H1(1
     )) @ Q2(1)=W1(1)*A1/(V1(1)*
     A2) @ H=(1000*H1(1)+W0^2/2)
     /1000
2390 IF H0>=H THEN F=1 @ PRINT T
     AB(3);"Flow chockes as it f
     lashes" ELSE 2730
2400 P1(3)=P1(1) @ T1(3)=T1(1) @
      H1(3)=H1(1) @ V1(3)=V1(1)
     @ W1(3)=FNW(H1(3))
2410 Q2(3)=W1(3)*A1/(V1(3)*A2) @
      PRINT @ PRINT TAB(2);"Choc
     king cond. = Flash cond." @
      PRINT
2420 GOSUB 4390
2430 GOSUB 4370
2440 GOSUB 4210
2450 Q=Q2(3) @ GOSUB 4030
2460 P0(3)=Y(3) @ S0(3)=Y(5) @ T
     0(3)=Y(2)
2470 P2=P0(3) @ GOSUB 3810
2480 IF P=P1(3) THEN F1=2 @ P2(3
     )=P0(3) @ S2(3)=S0(3) ELSE
     2540
2490 GOSUB 3420
2500 PRINT TAB(10);C$;P1(3);S$ @
      PRINT TAB(10);D$;P2(3);S$
     @ GOSUB 3440
2510 GOSUB 3450
2520 PRINT TAB(10);D$;P2(3);S$ @
      GOSUB 3480
2530 GOTO 320
2540 IF P<P1(3) THEN F1=3 @ P1=P
     1(3) @ GOSUB 3510 ELSE 2630
2550 P2(3)=P2 @ S2(3)=Y(5)
2560 P2=P0(3) @ GOSUB 3810
2570 P3=P @ GOSUB 3420
2580 PRINT TAB(10);C$;P1(3);S$ @
      PRINT TAB(10);D$;P2(3);L$
     @ GOSUB 3440
2590 GOSUB 3450
2600 PRINT TAB(10);D$;P2(3);L$ @
      GOSUB 3470
2610 GOSUB 3480
2620 GOTO 320
2630 IF P>P1(3) THEN F1=1 @ P2=P
     1(3) @ K=3 @ GOSUB 3060
2640 X2(3)=Y(1) @ P1=P1(3) @ GOS
     UB 3630
2650 P2(3)=P2 @ S2(3)=Y(5)
2660 GOSUB 4300
2670 GOSUB 3420
2680 PRINT TAB(10);C$;P1(3);L$ @
      PRINT TAB(10);D$;P0(3);S$
     @ PRINT F$
2690 PRINT TAB(10);C$;P1(3);S$ @
      PRINT TAB(10);D$;P2(3);T$
     @ GOSUB 3440
2700 GOSUB 3450
2710 PRINT TAB(10);D$;P2(3);T$ @
      GOSUB 3480
2720 GOTO 320
2730 IF H1(1)<H0 AND H0<H THEN F
     =2 @ GOSUB 4060
2740 PRINT TAB(6);"Chocking cond
     itions" @ PRINT
2750 PRINT TAB(8);"Pc=";P1(3) @
     PRINT TAB(8);"Tc=";T1(3) @
     PRINT TAB(8);"hc=";H1(3)
2760 PRINT TAB(8);"sc=";S0 @ PRI
     NT TAB(8);"vc=";V1(3) @ IF
     F=3 THEN RETURN
2770 GOSUB 4390
2780 GOSUB 4370
2790 Q2(3)=W1(3)*A1/(V1(3)*A2) @
      GOSUB 4210
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2800 Q=Q2(3) @ GOSUB 4030
2810 P0(3)=Y(3) @ S0(3)=Y(5) @ T
     0(3)=Y(2) @ P2=P0(3) @ GOSU
     B 3810
2820 IF P=P1(3) THEN F1=2 @ P2(3
     )=P0(3) @ S2(3)=S0(3) ELSE
     2900
2830 P1=P1(1) @ GOSUB 3510
2840 P2(1)=P2 @ S2(1)=Y(5) @ GOS
     UB 3420
2850 PRINT TAB(10);C$;P1(1);S$ @
      PRINT TAB(10),D$;P2(1);L$
     @ PRINT F$
2860 PRINT TAB(10);C$;P1(3);T$ @
      PRINT TAB(10);D$;P2(3);S$
     @ GOSUB 3440
2870 GOSUB 3460
2880 PRINT TAB(10);D$;P2(3);S$ @
      GOSUB 3480
2890 GOTO 320
2900 IF P<P1(3) THEN F1=3 @ P1=P
     1(3) @ GOSUB 3560 ELSE 3000
2910 P2(3)=P2 @ S2(3)=Y(5) @ P1=
     P1(1) @ GOSUB 3510
2920 P2(1)=P2 @ S2(1)=Y(5) @ P2=
     P0(3) @ GOSUB 3610
2930 P3=P @ GOSUB 3420
2940 PRINT TAB(10);C$;P1(1);S$ @
      PRINT TAB(10);D$;P2(1);L$
     @ PRINT F$
2950 PRINT TAB(10);C$;P1(3);T$ @
      PRINT TAB(10),D$;P2(3);L$
     @ GOSUB 3440
2960 GOSUB 3460
2970 PRINT TAB(10);D$;P2(3);L$ @
      GOSUB 3470
2980 GOSUB 3480
2990 GOTO 320
3000 IF P>P1(3) THEN F1=1 @ P2=P
     1(3) @ K=3 @ GOSUB 3860
3010 X2(3)=Y(1) @ P1=P1(3) @ GOS
     UB 3630
3020 P2(3)=P2 @ S2(3)=Y(5)
3030 Q=Q2(1) @ L=10^3*P1(1)+W1(1
     )*Q @ L=IP(L*10^3)/10^3 @ G
     OSUB 4030
3040 P2=Y(3) @ L1=10^3*P2+W2*Q @
      L1=IP(L1*10^3)/10^3
3050 IF L1=L THEN F2=2 @ P1(2)=P
     1(1) @ P0(2)=P2 @ S0(2)=Y(5
     ) ELSE 3090
3060 GOSUB 3420
3070 PRINT TAB(10);C$;P1(1);S$ @
      PRINT TAB(10),D$;P0(2);S$
     @ GOSUB 3490
3080 GOTO 3200
3090 IF L1<L THEN F2=1 @ GOSUB 3
     940 ELSE 3150
3100 P1=P1(1) @ GOSUB 3510
3110 P2(1)=P2 @ S2(1)=Y(5) @ GOS
     UB 3420
3120 PRINT TAB(10);C$;P1(1);S$ @
      PRINT TAB(10);D$;P2(1);L$
     @ PRINT F$
3130 PRINT TAB(10);C$;P1(2);T$ @
      PRINT TAB(10),D$;P0(2);S$
     @ GOSUB 3490
3140 GOTO 3200
3150 IF L1>L THEN F2=3 @ GOSUB 4
     300
3160 P1=P1(1) @ GOSUB 3630
3170 P2(1)=P2 @ S2(1)=Y(5) @ GOS
     UB 3420
3180 PRINT TAB(10);C$;P1(2);L$ @
      PRINT TAB(10),D$;P0(2);S$
     @ PRINT F$
3190 PRINT TAB(10);C$;P1(1);S$ @
      PRINT TAB(10);D$;P2(1);T$
     @ GOSUB 3490
3200 GOSUB 3440
3210 GOSUB 3460
3220 PRINT TAB(10);C$;P1(3);T$ @
      GOSUB 3480
3230 GOTO 320
3240 F=3 @ T1(1)=T0 @ GOSUB 4060
3250 Q2(3)=W1(3)*A1/(V1(3)*A2) @
      P0(3)=P0 @ P0(2)=P0 @ P1(1
     )=P0 @ GOSUB 4210
3260 P2=P1(3) @ K=3 @ Q=Q2(3) @
     GOSUB 3860
3270 X2(3)=Y(1) @ P1=P1(3) @ GOS
     UB 3630
3280 P2(3)=P2 @ S2(3)=Y(5)
3290 PRINT TAB(1);"Entire flow i
     n Two Phase region" @ PRINT
3300 GOSUB 2740
3310 IF Y$="S" THEN N$=S$ @ GOTO
      3340
3320 N$=T$ @ PRINT @ GOSUB 4370
3330 GOTO 3350
3340 PRINT TAB(3);"M*=0" @ PRINT
      TAB(3);"J/J*=0" @ PRINT @
     GOSUB 4370
3350 PRINT @ PRINT TAB(10);A$ @
     PRINT E$ @ PRINT TAB(10),C$
     ;P0;N$ @ PRINT TAB(10),D$;P
     0;N$
3360 GOSUB 3490
3370 PRINT @ PRINT TAB(11);B$ @
     PRINT E$
3380 PRINT TAB(10),C$;P1(3);T$ @
      PRINT TAB(10),D$,P2(3);T$
3390 GOSUB 3480
3400 GOTO 320
3410 ! Subroutine for output #1
      ******************************
3420 PRINT @ PRINT TAB(10),A$ @
     PRINT E$
3430 PRINT TAB(10),C$;P0;L$ @ PR
     INT TAB(10);D$,P0;L$ @ PRIN
     T F$ @ RETURN
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3440 PRINT @ PRINT TAB(11);B$ @
     PRINT E$ @ RETURN
3450 PRINT TAB(10);G$;P1(3);S$ @
      RETURN
3460 PRINT TAB(10);G$;P1(3);T$ @
      RETURN
3470 PRINT F$ @ PRINT TAB(10);G$
     ;P3;T$ @ PRINT TAB(10);D$;P
     0(3);S$ @ RETURN
3480 PRINT F$ @ PRINT TAB(10);G$
     ;P4;T$ @ PRINT TAB(10);D$;P
     2(4);T$ @ RETURN
3490 PRINT F$ @ PRINT TAB(10);C$
     ;P1(3);T$ @ PRINT TAB(10);D
     $;P2(3);T$ @ RETURN
3500 ! ****** Subroutines ******
3510 W1=FNW3(P1) @ Q=W1*A1/(V0*A
     2)
3520 W2=Q*V0 @ P2=(10^3*P1-Q*(W2
     -W1))/10^3
3530 Y(3)=P2 @ Y(2)=T1(1) @ I=23
      @ GOSUB 1530
3540 RETURN
3550 ! ........................
3560 IF P1=P1(3) THEN W1=W1(3) @
      Q=Q2(3) @ GOTO 3590
3570 Y(3)=P1 @ Y(5)=S0 @ I=35 @
     GOSUB 1530
3580 W1=FNW(Y(4)) @ Q=W1*A1/(Y(6
     )*A2)
3590 W2=Q*V0 @ P2=(10^3*P1-Q*(W2
     -W1))/10^3
3600 Y(3)=P2 @ Y(2)=T0(3) @ I=23
      @ GOSUB 1530
3610 RETURN
3620 ! ........................
3630 IF P1=P1(1) THEN W1=FNW(H1(
     1)) @ Q=W1*A1/(V1(1)*A2) @
     GOTO 3670
3640 IF P1>P1(1) THEN W1=FNW3(P1
     ) @ Q=W1*A1/(V0*A2) @ GOTO
     3670
3650 IF P1<P1(1) THEN I=35 @ Y(3
     )=P1 @ Y(5)=S0 @ GOSUB 1530
3660 W1=FNW(Y(4)) @ Q=W1*A1/(Y(6
     )*A2)
3670 L=1000*P1+Q*W1 @ L=IP(L*10)
     /10 @ IF F=3 THEN Y(3)=P0 E
     LSE GOSUB 4030
3680 K2=Y(3) @ R1(1)=0
3690 K1=P1(3) @ R2(1)=X2(3) @ R2
     =X2(3) @ R1=0 @ K=3 @ GOTO
     3740
3700 L1=1000*P2+Q*W2 @ L1=IP(L1*
     10)/10
3710 IF L1=L THEN RETURN
3720 IF L1>L THEN K2=P2 @ R1=R @
      R1(1)=R @ R2=R2(1) @ GOTO
     3740
3730 IF L1<L THEN K1=P2 @ R2=R @
      R2(1)=R @ R1=P1(1)
3740 P2=(K1+K2)/2 @ R=(R1+R2)/2
      @ GOSUB 3910
3750 GOTO 3700
3760 ! ........................
3770 IF P2=P2(4) THEN GOTO 3790
3780 K=6 @ Q=Q2(3) @ GOSUB 3860
3790 P=FNZ(P2) @ RETURN
3800 ! ........................
3810 W2=Q2(3)*V0 @ P=FNZ(P2)
3820 IF P2=P0(3) THEN 3840
3830 Y(3)=P2 @ Y(2)=T0(3) @ I=23
      @ GOSUB 1530
3840 RETURN
3850 ! ........................
3860 R1=0 @ R2=1 @ R=(R1+R2)/2 @
      GOTO 3910
3870 W2=Q*Y(6) @ J=1000*(H0-Y(4)
     )-W2^2/2 @ J=IP(10^K*J)
3880 IF J=0 THEN RETURN
3890 IF J<0 THEN R2=R @ R=(R+R1)
     /2 @ GOTO 3910
3900 IF J>0 THEN R1=R @ R=(R+R2)
     /2
3910 Y(1)=R @ Y(3)=P2 @ I=13 @ G
     OSUB 1530
3920 GOTO 3870
3930 ! ........................
3940 K2=P1(1) @ K1=P1(3) @ GOTO
     4000
3950 W1=FNW(Y(4)) @ Q=W1*A1/(Y(6
     )*A2) @ L=10^3*P1+W1*Q @ L=
     IP(L*10)/10 @ GOSUB 4030
3960 P2=Y(3) @ L1=1000*P2+Q*W2 @
      L1=IP(L1*10)/10
3970 IF L1=L THEN P1(2)=P1 @ P0(
     2)=P2 @ S0(2)=Y(5) @ RETURN
3980 IF L1>L THEN K1=P1 @ GOTO 4
     000
3990 IF L1<L THEN K2=P1
4000 P1=(K1+K2)/2 @ I=35 @ Y(3)=
     P1 @ Y(5)=S0 @ GOSUB 1530
4010 GOTO 3950
4020 ! ........................
4030 W2=Q*V0 @ H2=(H0*1000-W2^2/
     2)/1000 @ Y(1)=0 @ Y(4)=H2
     @ I=14 @ GOSUB 1530
4040 RETURN
4050 ! ........................
4060 T2=T1(1) @ IF F=3 THEN M1=0
      @ T1=T0 @ GOTO 4100 ELSE T
     1=T1(1) @ Y(2)=T1 @ Y(5)=S0
      @ I=25
4070 GOSUB 1530
4080 GOSUB 1450
4090 W1(3)=FNW(Y(4)) @ M1=W1(3)/
     Y(7)
4100 T2=T2-5 @ Y(2)=T2 @ Y(5)=S0
      @ I=25 @ GOSUB 1530
4110 GOSUB 1450
```

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4120 W1(3)=FNW(Y(4)) @ M2=W1(3)/
     Y(7) @ IF M2<1 THEN GOTO 41
     00
4130 IF IP(M2*10^4)/10^4=1 THEN
     M=M2 @ GOTO 4140 ELSE GOTO
     4170
4140 IF M=1 THEN T1(3)=Y(2) @ P1
     (3)=Y(3) @ H1(3)=Y(4) @ V1(
     3)=Y(6) @ RETURN
4150 IF M>1 THEN T2=Y(2) @ M2=M
     @ GOTO 4170
4160 IF M<1 THEN T1=Y(2) @ M1=M
4170 Y(2)=(1-M2)*(T1-T2)/(M1-M2)
     +T2 @ Y(5)=S0 @ I=25 @ GOSU
     B 1530
4180 GOSUB 1450
4190 W1(3)=FNW(Y(4)) @ M=W1(3)/Y
     (7) @ M=IP(M*10^4)/10^4 @ G
     OTO 4140
4200 ! ..........................
4210 K1=0 @ K2=P1(3) @ Q=IP(Q2(3
     )*10)/10 @ P2=K2/2 @ GOTO 4
     270
4220 W2=FNW(Y(4)) @ Q1=W2/Y(6) @
      Q1=IP(Q1*10)/10
4230 IF Q1=Q THEN P2(4)=P2 @ GOS
     UB 3770 ELSE 4250
4240 P4=P @ RETURN
4250 IF Q1>Q THEN K2=P2 @ P2=(P2
     +K1)/2 @ GOTO 4270
4260 IF Q1<Q THEN K1=P2 @ P2=(P2
     +K2)/2
4270 I=35 @ Y(3)=P2 @ Y(5)=S0 @
     GOSUB 1530
4280 GOTO 4220
4290 ! ..........................
4300 K1=P1(1) @ K2=P0
4310 P1=(K1+K2)/2 @ W1=FNW3(P1)
     @ Q=W1*A1/(V0*A2) @ L=10^3*
     P1+Q*W1 @ L=IP(L*10)/10 @ G
     OSUB 4030
4320 L1=10^3*Y(3)+Q*W2 @ L1=IP(L
     1*10)/10
4330 IF L1=L THEN P1(2)=P1 @ P0(
     2)=Y(3) @ S0(2)=Y(5) @ RETU
     RN
4340 IF L1>L THEN K1=P1 @ GOTO 4
     310
4350 IF L1<L THEN K2=P1 @ GOTO 4
     310
4360 ! ..........................
4370 FOR O=1 TO 32 @ PRINT TAB(O
     );"*"; @ NEXT O @ PRINT
4380 RETURN
4390 DG=W1(1)/W0 @ PRINT TAB(8),
     "M*=";DG @ PRINT TAB(8),"J/
     J*=";DG @ PRINT @ RETURN
4400 DEF FNH(X) = (X/2*.0254)^2*
     PI
4410 DEF FNW(X) = SQR(2000*(H0-X
     ))
4420 DEF FNW3(X) = SQR(2000*V0*(
     P0-X))
4430 DEF FNZ(X) = (Q2(3)*A2*(W2-
     W1(3))+10^3*(X*A2-P1(3)*A1)
     )/(10^3*(A2-A1))
4440 END
```

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